A SUPPLY-LIMITED MODEL FOR COLD-AEOLIAN ACTIVITY

by

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Abstract

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Aeolian activity which occurs under sub-zero temperatures over frozen sediment is termed cold-aeolian. These phenomena are found in seasonally and perennially cold regions. Cold-aeolian processes effect significant amounts of sediment movement, produce distinctive cold-season landscapes and develop striking depositional features. Research on cold-aeolian phenomena has been largely qualitative and fragmented to this point. Quantitative field measurements of processes are extremely rare.

This dissertation uses controlled experiments and field measurements to generate a model for cold-aeolian activity. Wind erosion of frozen sediments is governed by pore-ice cohesion which limits the supply of sediments to aeolian processes. Controlled-temperature experiments explore the relationship between surface temperature and water content, delineating the cohesion boundaries for various aeolian processes. Small amounts of frozen pore-water can exert considerable restrictions on sediment movement. In the context of these limitations, pore-ice sublimation is the mechanism by which sediments are released from the surface and become available to entrainment by wind. Field experiments define the rate of particle release in terms of microclimate and surface conditions. The quantitative information on the supply limitations of pore-ice cohesion and the supply mechanisms of pore-ice sublimation are incorporated into a general model of cold-aeolian activity. Other limits to movement in the cold environment, such as snow and ice cover, are also included in the assessment of aeolian activity. Winter field measurements from Presqu'ile Beach on the north shore of Lake Ontario provide data to test model accuracy. There is reasonable agreement between model predictions and field measurements, but the results point to the need for more research.

The dissertation is a significant body of work within the field of cold-aeolian research. Field measurements have produced quantitative information which is unprecedented in the study of cold-region aeolian activity. These measurements demonstrate that cold-aeolian processes account for a significant amount of sediment movement and geomorphic change, both readily visible in the Presqu'ile beach and dune complex. The model, presented as a computer simulation, is a practical tool for both managers and researchers. The model also serves as a conceptual framework for cold-aeolian activity and can play an important role in integrating this new field of research with mainstream aeolian geomorphology.

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I would like to acknowledge the many people who contributed to this work through their wise advice, cheerful field work, and timely encouragement. It would have been impossible to complete this thesis without their contributions.

I am grateful to my advisors at the University of Waterloo for encouraging my investigations and asking pointed questions at all the right times. Dr. Jane Irvine provided much needed research equipment and her enthusiasm for field research. Dr. Ellsworth LeDrew was always willing to discuss tricky details, and his critical comments on the thesis draft were especially insightful. A special thank you to Dr. Ian McKenzie for his cheerful assistance, interest in my research, and wise advice.

Many people helped with the field research at Presqu'ile Beach. Caralyn Kelly has been my chief field assistant despite her own heavy workload. Her skills at surveying, setting up the weather tower, pounding stakes into the beach, and cooking supper were much appreciated. Kevin Misurak was invaluable in setting up the weather tower under 'challenging' conditions for two years in a row; his technical advice was always welcome. Additional help with field work was cheerfully provided by my brothers Micah and John, Jennifer Ellis, Kelly Foley and others. I am also grateful to the people who donated the toilet paper rolls, empty milk cartons and pantyhose from which 'scientific' equipment was born.

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To my father,

whose example is an inspiration.

Who is this? Even the wind and the waves obey him!

Mark 4:41b

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Chapter One

INTRODUCTION

To see a world in a grain of sand...
William Blake

Wind as a geographic agent of erosion, transport and deposition has been studied in earnest for less than a century. Aeolian geomorphology is a relatively young discipline compared to fluvial or glacial geomorphology; its youth results largely from persistent beliefs that landscapes are shaped by water, not wind. It was not until the 1940's that Bagnold's research laid a solid foundation for aeolian studies (Bagnold 1941). His work may not be directly responsible for the increasing interest in wind processes over the next fifty years, but it certainly set the tone and direction for research. The surge of interest in the past few decades--illustrated by a geometric increase in volume of literature--has several causes: well-funded space research sought earth analogues for other planetary aeolian features, better technology improved measurements in harsh aeolian environments, and recent advancements in earth observations showed the enormous extent of aeolian landforms (Livingstone and Warren 1996, 1). Despite the attention, phrases such as "very little is known about" and "not yet understood" appear with monotonous regularity in discussions of particle entrainment, transport equations, particle-surface impact, influences of moisture content, and so on. The lack of information can be frustrating at times, but it also lends vibrancy to a discipline filled with an endless supply of questions and the frequent thrill of discovery.

On one leading fringe of wind-based research is an upstart field of investigation into aeolian processes and formations in cold environments. In the 1980's, gathered evidence shattered the mistaken but widely-held assumption that ground-freezing immobilizes sediments until warmer temperatures prevail (see, for example, Carson and MacLean 1986; McKenna Neuman and Gilbert 1986; Marsh and Marsh 1987; Koster 1988; Koster and Dijkmans 1988; Law 1989b. Rosen (1978) and Goldsmith (1985) claim that sand movement does not occur on frozen beaches and dunes in winter). Not only was there the indisputable occurrence of niveo-aeolian features and substantial topographic change over winter months, but the research further pointed to efficient mechanisms for detaching particles from cohesive frozen surfaces. An entire vista of unexplored processes and forms lay before aeolian geomorphology and investigators started moving into the new territory. In some ways the research did not stray far from traditional aeolian geomorphology, with its emphasis on environmental conditions imposed on the ideal loose homogeneous horizontal surface. Nevertheless, new variables of snow, frozen moisture and firmly cemented grains were unique to the cold-aeolian environment. In 1998, not much time has passed since cold-climate sediment movement was 'discovered', and if aeolian geomorphology can be called youthful, cold aeolian research is barely out of its infancy.

1.1 The Research Problem

As the literature review in chapter two will demonstrate, cold-aeolian research is characterized by an emphasis on form rather than process, by isolated studies, and by the lack of a coherent framework. While the where's, when's and what's of aeolian erosion and deposition in cold environments are being addressed, the how's are lagging far behind, overwhelmed by both the enormity and the vagueness of the question. There are far too few quantitative and process-oriented studies on the mechanisms of detaching sediments from frozen cohesive surfaces and the aeolian transport which results. Furthermore, in the existing shot-gun approach to quantitative investigations, important directions for research may be entirely overlooked because they lie outside the scope of individual studies. There are relatively few links between existing studies because there is no quantitative, coherent framework for cold-aeolian processes. Outsider perception of the wind's role in cold environments is weakened by the lack of consensus. Significant areas for further investigation are as yet undefined and contemporary research remains on the periphery of aeolian geomorphology.

1.2 Purpose and Objectives

The purpose for this study is twofold: to obtain quantitative information on the processes of sediment entrainment from frozen surfaces, and to incorporate that information into a general model of cold-aeolian processes. The model should integrate entrainment and transport mechanisms with the environmental conditions posed by cold temperatures and frozen moisture. Some quantitative relationships necessary to the model are not available from previous research, and experiments were designed to obtain this information. As a result, the specific objectives of the study are to:

1. define frozen sediment influences on cold-aeolian entrainment through controlled-temperature tests on surface cohesion,
2. predict sediment supply from frozen surfaces through field experiments measuring local microclimate conditions and frozen surface erosion,
3. produce a comprehensive model for cold-aeolian activity based on the supply limitations posed by the surface and sediment supply produced by local conditions,
4. assess the accuracy of the model by testing model predictions against field measurements of sand movement and deflation from natural beach sites, and
5. set the model and field observations into the context of seasonal beach and dune change.

While the dissertation's primary focus is producing an accurate and useful model for cold-aeolian processes, the experimental data and quantitative field measurements in themselves make a significant contribution to the research field.

1.3 Study Components

The dissertation research is divided into five distinct components based on the study objectives. The components provide a manageable framework for gathering and analysing data, and they are identified as (1) controlled-temperature tests, (2) field experiments, (3) model-building, (4) model-testing, and (5) study context. Each component deals with some aspect of developing the model, whether it is defining relationships through experiments, directly working on model construction, or assessing the model's accuracy and larger context. Each component also shares common goals of quantifying processes and clarifying wind action in cold environments.

An important first step in defining model relationships is the investigation of frozen-surface cohesion. Loose dry sand, even when it is frozen, has no cohesion. In contrast, frozen sand that is not dry contains pore ice which cements the sand grains together and increases their resistance to entrainment by wind. The pore-ice cohesion, which influences sediment resistance to movement, depends on the amount and temperature of frozen moisture in the pore spaces. Little information exists on how cohesion changes with moisture and temperature despite the importance of cohesion in determining whether or not sand can be entrained from the surface. To obtain this information for the model, experiments under controlled temperatures--using frozen samples with a range of water contents--define the relationship between cohesion, water content, and temperature. The result is a moisture-based classification for frozen sands in which aeolian processes are related to surface water contents.

Another important but poorly-defined aspect of cold-aeolian processes is the relationship between microclimate and sediment supply. The controlled-temperature experiments demonstrate that surface cohesion is too great for sand to be directly entrained by the wind when certain water contents are exceeded. Over time, the cementation of surface grains decreases as sublimation reduces the amount of ice in the pore spaces. New experiments build upon previous research which demonstrated that wind speed, temperature and relative humidity determine the rate at which sand grains are loosened. The new experiments define an equation in which the supply of loose sediments is predicted from the microclimate variables. Additional experiments relate a range of water contents to the release of frozen sediments. The amount of sand which can be released from the frozen surface controls total transport in the cold, humid beach environment.

The premise for the model of cold-aeolian processes is apparent in the aforementioned experiments: aeolian activity in cold environments is controlled by surface and microclimate conditions. Under sub-zero temperatures, three broad types of beach activity are possible: 1) a buffer of snow or ice between frozen sand and the wind prevents erosion, 2) pore-ice sublimation loosens exposed sand grains at the surface but the grains are not moved because wind speeds are too low, or 3) strong winds effect the erosion, transport, and deposition of loosened sand grains. Each of these activities can be predicted from measurements of surface water content, temperature, wind speed, and relative humidity (and the converse--that the activities can predict what conditions exist--is also true). The conditions, processes and interactions are the building blocks of the cold-aeolian model which outlines possible combinations of conditions and predicts the resulting beach activity. Equations derived from the field experiments calculate the amounts of loose sand produced under various conditions, and the model predicts the total sand transported when the wind exceeds a critical threshold.

A model's validity is determined by the accuracy of its predictions. Simultaneous measurements of microclimate/surface variables with observed beach activity and sand movement provide the data for testing the model. With microclimate and surface conditions as model inputs, predictions are generated and compared to observed activity and measured sand transport. The comparisons illustrate the model's potential for accurate and useful predictions of cold-aeolian activity.

Any discussion of cold-aeolian processes would be incomplete without mention of the contexts in which they operate. Within the cold season, there is a distinctly spatial component to aeolian activity and sand transport. Varying conditions over the beach and dune complex ensure that certain areas will experience enhanced erosion whereas other areas become habitual deposition zones. The cold-aeolian processes act alongside other winter processes such as water erosion, freeze-thaw activity, ice-push and ice-rafting, and so on. On a larger scale, the winter processes contribute to annual sediment movement on the beach and dunes. The distinctive winter results of cold-aeolian activity, such as beach erosion, dune growth, and niveo-aeolian deposits, play important roles in the yearly and long-term changes of the beach and dunes.

1.4 Study Area

The site for field experiments and measurements is located on the north shore of Lake Ontario at Presqu'ile Beach (figure 1.1). The site was chosen for its cold-aeolian activity (Law 1990; van Dijk 1993), the accessibility of the beach and dunes during the cold season, and the proximity of a research station for accommodations and laboratory work. Cold-aeolian processes on the beach and dunes are representative of processes in other cold regions, although the frequency, magnitude and direction of sediment movement result from specific conditions at the site. In chapter nine, Presqu'ile measurements will be compared to measurements from other cold regions.

The large sandy beach in Presqu'ile Provincial Park is oriented approximately north-south along its 2.4-kilometre length and ranges in width from 40 to 120 m. Most of the field work took place at the northern end of the beach (figure 1.2)--designated Beach One by park staff--where the beach has an azimuth of 320° from north and an approximate width of 95 m. Managed by the province of Ontario as part of Presqu'ile Provincial Park, the beach has a rich geological history culminating in the present-day conditions and active geomorphic processes important to current land-use.

Beach-forming processes--still active today--began as Lake Ontario levels stabilized 5000 to 3500 years ago (Law 1989a). After deglaciation and the transformation of glacial Lake Iroquois to Lake Ontario, all the ingredients for tombolo development were present in the Presqu'ile area: a small offshore island, a narrow channel between the island and the mainland, and a large underwater sediment deposit updrift of the channel. The glacial and glacio-fluvial sediments were reworked by waves and carried inshore and eastward by longshore currents. Material was deposited when the sediments reached the channel and shallow water reduced wave and current energy. A series of recurved spits grew out from the mainland and the island, eventually joining to form a tombolo (Ernsting 1976).

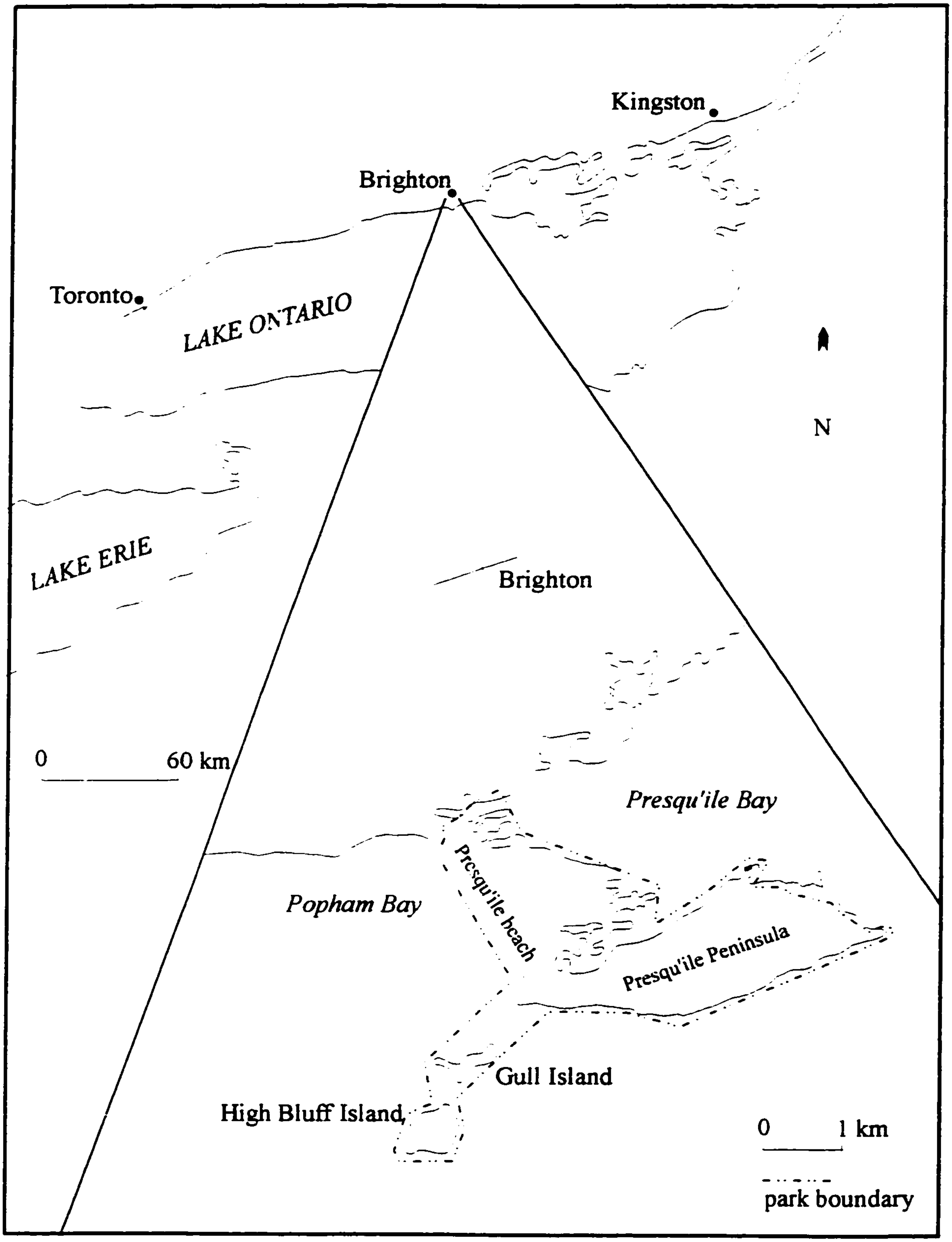


Figure 1.1 Location of Presqu'ile Provincial Park, Ontario

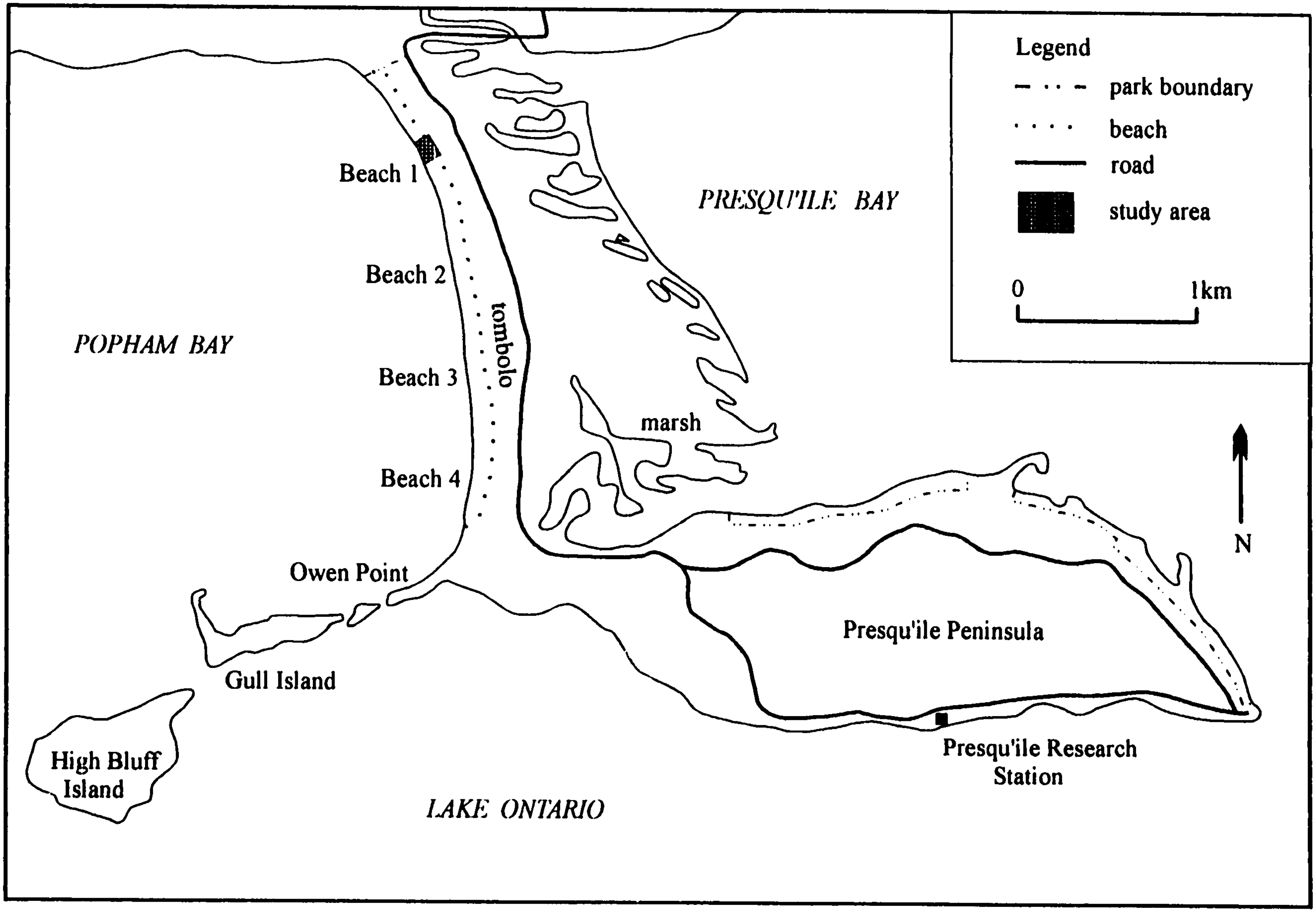


Figure 1.2 Study area in Presqu'ile Provincial Park, Ontario

Wave-borne sediment was trapped at the head of the newly-formed Popham Bay and an arcuate beach began to develop (Law 1989a, 18). As more sediments were added, the beach grew steadily westward. Accretion continues to this day with rates estimated at 2 metres per year between 1949 and 1986 (Law 1989a, 26).

Beach material is primarily wave-deposited fine quartzite sands. The sediments have a narrow range of sizes (figure 1.3) and the average grain diameter decreases slightly from 0.21 mm at the north end of the beach to 0.16 mm at the south end (Menhennet 1994). Grain shape is sub-angular to sub-rounded on Beach One (Pechkovsky 1994) and becomes well-rounded further south (Menhennet 1994). While these changes are slight, they are consistent with nearshore littoral processes which cause differential sorting and increase particle rounding as sediments move alongshore from north to south. Onshore, the beach slope dips at less than 2° towards the lake, and bedding layers parallel to the slope are apparent from the differential sorting of the heavy mineral fraction (Law 1989a, 33). Windblown fragments of zebra mussels were observed across the beach and foredunes in

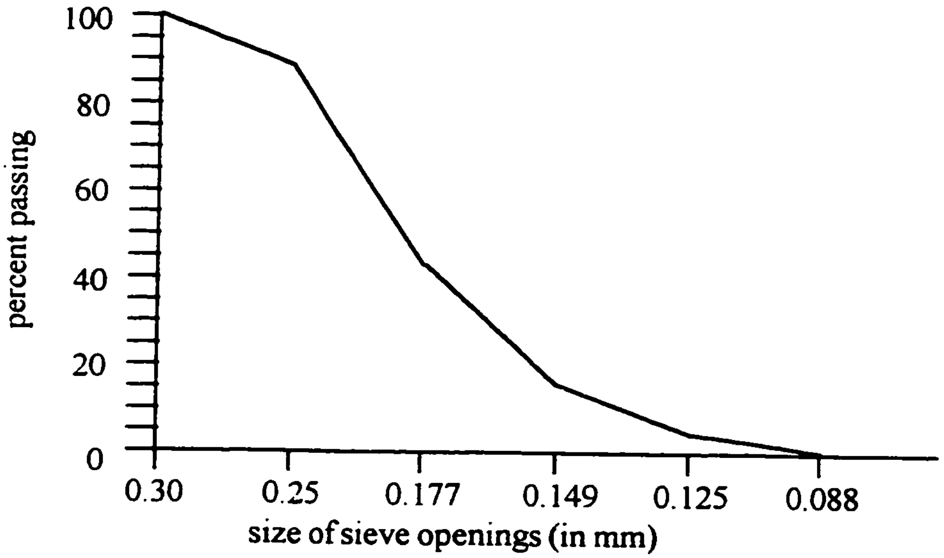
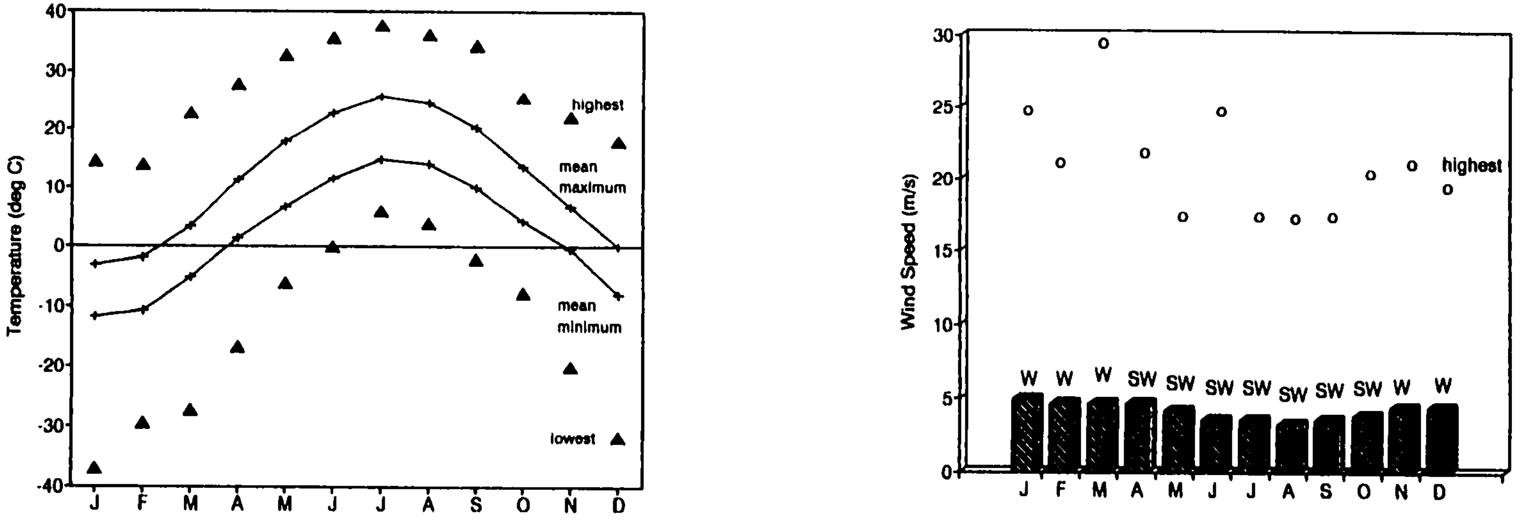


Figure 1.3 Grain-size distribution of beach sediments from Presqu'ile beach one (after Menhennet 1994)

early 1997, four years after the mussels were noticed in Popham Bay; occurrence of the shell fragments is of note as a new addition to the stratigraphic record (McKenzie 1997, personal communication).

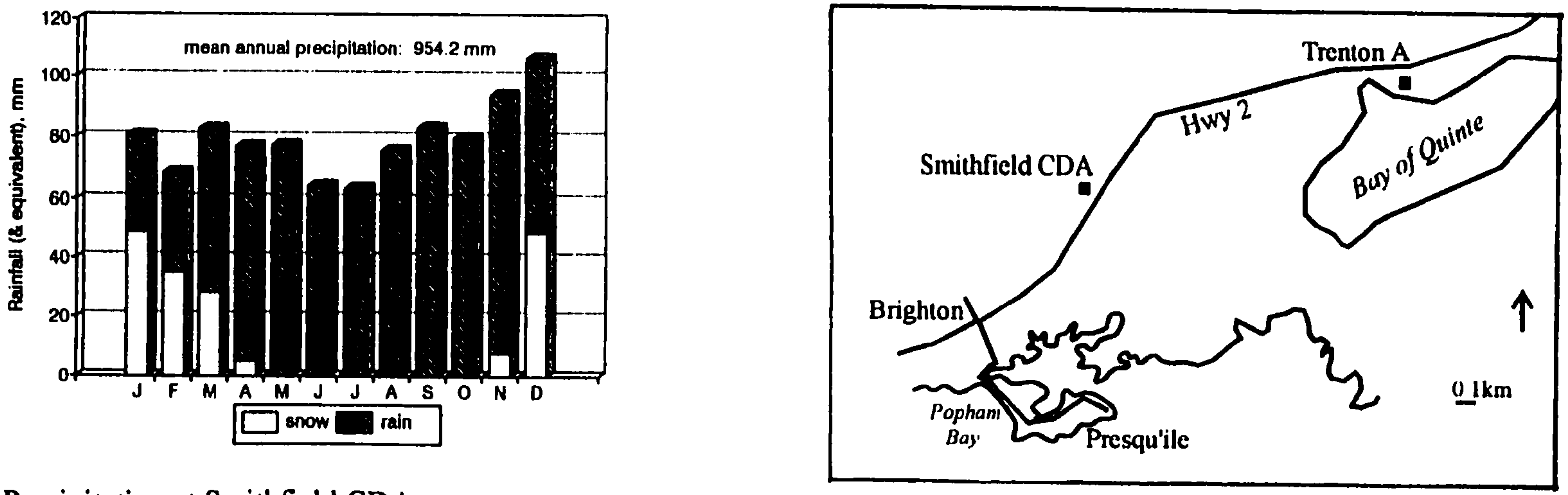
The topography of onshore sediments has been largely determined by wind action supplemented with park management practices. Strong winds moving over the beach entrain sediments, transport them inland and deposit them behind vegetation and other obstacles where wind energy is diminished. Because Presqu'ile is a rapidly prograding beach with active onshore movement of sand, one would expect the succession of dune ridges (each suggesting an abandoned shoreline) to extend to the current high-water mark (Bird 1990). However, the central portion of the Presqu'ile beach is mechanically raked during summer months to provide recreational users with a visually pristine and vegetation-free surface. As a result, vegetation growth and dune formation have been limited to an area unnaturally far from the water's edge. In recent years the raking practices have been combined with dune formation to protect beach parking lots. Essentially, the management practices have altered the spacing and timing of natural formations by creating a larger area of erosion (the beach) and limiting deposition to one foredune. The single foredune contrasts the sequential series of dunes which are found to the north of Beach One and to the south of Beach Three. While landscape form has been changed by management practices, the processes of aeolian erosion, transport and deposition remain largely unaffected because they are dominant in the recreational off-season.

Presqu'ile Beach experiences distinct seasons as part of its cold, boreal-forest climate. Information derived from the thirty-year climate normals recorded at nearby stations are graphically represented in figure 1.4. Distinct warm and cold seasons are apparent, with temperatures ranging from an average daily low of -11.8°C in January to an average daily high of 25.7°C in July. Freezing temperatures are possible from late October through April. Consistent with its coastal nature, the area receives moderate amounts of precipitation yearly--in the form of rain during the warmer months, and as both rain and



a) Temperatures at Smithfield CDA

c) Wind speed and direction at Trenton Station A



b) Precipitation at Smithfield CDA

d) Measurement locations with respect to Presqu'ile

Figure 1.4 Climatic graphs and measurement locations for the Presqu'ile area, Ontario; data are derived from 30-year climate normals, 1961-1990 (Environment Canada 1993) snow during the cold season. Relative humidity is not represented in the graphs but ranges from 50% to 100% throughout the year. Seasonal patterns of wind occur with relatively stronger westerly winds from November through March and slightly weaker winds from the southwest during the summer months.

The annual variations in climate produce aeolian processes which are seasonal in nature. Only small amounts of sand are moved by wind during the summer months when average and maximum winds are less strong. In contrast, the strong winter winds from the west combine with seasonal dieback of deciduous vegetation to move substantial amounts of sand from the beach onto and over the foredunes (Law 1990). Formation of an icefoot at the water's edge heightens beach erosion by preventing wave action from replenishing the sand supply. Because no sediment is being added to the system, it is easier to measure changes in sediment location. When the icefoot breaks up in the spring, eroded material is quickly replaced by wave-borne sediments. Aeolian activity in the spring and fall lies somewhere between the summer and winter extremes, although spring melt conditions literally dampen the likelihood of movement.

The Ministry of Natural Resources and Presqu'ile Provincial Park staff have a vested interest in understanding the geomorphic processes at work on the Presqu'ile Beach. Two objectives from the Ministry of Natural Resources Business Plan for Ontario Parks are "to protect natural heritage and biological features of provincial significance" and "to provide for a wide range of outdoor recreational opportunities" (Government of Ontario 1997, 2). Balancing protection of the active beach and dune complex with the recreational needs of thousands of visitors who use the beach each summer demands strategic management. An understanding of the cold-aeolian processes responsible for beach and dune change is vital to the park's effective and responsible management. The processes themselves contribute to the provincial significance of the natural environment, and therefore have an important place in summer interpretive programs.

1.5 Summary

The young field of cold-aeolian research remains fragmented and lacks quantitative research into the processes of sediment movement. In response, the current study is designed to investigate sediment entrainment from frozen sand and to incorporate the quantitative results into a conceptual model for cold-aeolian processes. The study includes controlled-temperature testing of pore-ice cohesion and field experiments on sediment release by pore-ice sublimation. The primary goal of the study is to produce a model of cold-aeolian activity based on the interaction between environmental limitations and sediment supply. Field measurements of deflation and sediment movement are chosen to check model accuracy and provide a context for the study. The research is physically based on the north shore of Lake Ontario in Presqu'ile Provincial Park. The accessibility of measurement sites within the park and frequent movement of sediment during the cold season make the Presqu'ile Beach an ideal location for quantitative field research into cold-aeolian activity.

Chapter Two

CONCEPTUAL DEVELOPMENT OF COLD-AEOLIAN RESEARCH AND RATIONALE FOR THE PRESENT STUDY

> *When the wind blows, which seems to be most of the time...*
> Smith and Mertie (1930, 249)

Cold-aeolian research is a relatively new field of study despite distinct processes which visibly change landscapes. In this chapter, cold-aeolian literature is reviewed and evaluated according to common research themes. As the lack of a coherent research structure becomes apparent, the rationale for the present study is discussed. Two possible research directions are presented: the traditional transport-limited approach with its emphasis on wind-tunnel studies and a new supply-limited approach with an emphasis on environmental constraints. This study uses the supply-limited approach to develop a coherent framework for cold-aeolian phenomena.

2.1 Cold-Aeolian Literature

An assortment of studies, descriptions, and anecdotes constitute cold-aeolian literature at the current time. The disparate literature is listed by research location in table 2.1. Cold-aeolian phenomena are widespread and have been observed in environments ranging from Antarctica and the Arctic to Great Lake shorelines and inland sand dunes. A mere handful of studies have involved experiments under laboratory or field settings. Much of the literature centres on niveo-aeolian features and there are few direct observations of active processes.

Cold-aeolian phenomena are the aeolian forms and processes which occur when temperatures of the sediment surface and adjacent atmosphere fall below the freezing point (nominally 0°C). A number of distinct processes and landforms are featured. Notable differences from warm environments begin with ground freezing in which soil moisture immobilizes sediments by cementing them together. If temperatures remain below 0°C, soil particles can be released from the surface through pore-ice sublimation.

	Study	Location	(1) loose dry surfaces	(2) deflated surfaces	(3) sand movement	(4)niveo-aeolian deposits	(5) ventifacts (abrasion)
Antarctica	Cailleux 1972	McMurdo				x	
	Calkin and Rutford 1974	s. Victoria Land	x	x		x	x
	Miotke 1984	s. Victoria Land	x	x			x
	Hall 1989	s. Victoria Land	x				x
	Matsuoka et al. 1996	Sor Rondane Mtns					x
Arctic	Fristrup 1953	w. Greenland	x		x	x	x
	Wilson 1958	Finland				x	
	Pissart 1966, et al. 1977	n. Canada		x		x	
	Teeri and Barrett 1975	n. Canada				x	
	McKenna Neuman and Gilbert 1986	n. Canada	x	x		x	x
	Riezebos et al 1986	n. Norway	x	x		x	
	Swett and Mann 1986	e. Greenland				x	
	McKenna Neuman 1990a	n. Canada			x	x	x
	Dijkmans 1990a	w. Greenland	x		x	x	
	Dijkmans & Tornqvist 1991	w. Greenland	x	x		x	
	Lewkowicz and Young 1991	n. Canada		x		x	

...continued on page 17

	Study	Location	(1) loose dry surfaces	(2) deflated surfaces	(3) sand movement	(4)niveo-aeolian deposits	(5) ventifacts (abrasion)
Subarctic	Rochette & Cailleux 1971	n. Quebec				x	
	Cailleux 1972, 1974, 1976	n. Quebec				x	
	Filion and Morisset 1983	n. Quebec				x	
	Carson and MacLean 1986	nw. Saskatchewan	x				
	Filion and Marin 1988	n. Quebec				x	
	Koster and Dijkmans 1988	nw. Alaska				x	
	Dijkmans and Koster 1990	Alaska			x	x	
	Belanger and Filion 1991	n. Quebec				x	
	Ruz and Allard 1994	n. Quebec				x	
Other (alpine, coastal and inland)	Dozier et al. 1976	s.shore L. Superior		x		x	
	Ahlbrandt & Andrews 1978	Colorado				x	
	Ballantyne and Whittington 1987	nw Scotland				x	
	Marsh and Marsh 1987	n.shore L. Superior	x	x		x	
	Law 1990	n.shore L. Ontario	x	x	x	x	
	van Dijk 1993	n.shore L. Ontario	x	x	x	x	
	Hetu 1995	Gaspesie, Quebec				x	
experiments	Dijkmans and Mucher 1989	field experiments				x	
	McKenna Neuman 1989	cold laboratory					x
	McKenna Neuman 1990b	cold laboratory	x	x			
	van Dijk and Law 1995	field experiments	x	x			

Table 2.1. Cold aeolian phenomena recorded in the literature, including (1) desiccated and (2) deflated surfaces, (3) moving sand, (4) niveo-aeolian deposits, and (5) ventifacts or other abrasion features

Loosened grains can be entrained by wind and moved considerable distances. The frozen surface modifies saltation trajectories, and saltation, in turn, affects the frozen surface by entraining particles through impact. Transported sediments are deposited in areas of lower wind energy and produce stunning niveo-aeolian deposits when sand and snow are transported together, or sand and snow are deposited in interspersed layers. Cold-aeolian activity is also variously affected by decreased vegetation, discontinuous snow cover, surface ice and pebble-lag development. Singular morphologies ensue as erosion surfaces become wind-scoured and ice-cemented deposits maintain steep slope angles.

Niveo-aeolian deposits were first comprehensively described in the 1970's by Cailleux (1972, 1973, 1974, 1976; Rochette and Cailleux 1971) in the Quebec subarctic, and there has been a resurgence of interest in recent years (Koster 1988; Koster and Dijkmans 1988; Dijkmans 1990a; Belanger and Filion 1991; Ruz and Allard 1994). The distinctive sand and snow layers develop annually on aeolian depositional surfaces (Koster 1988; Dijkmans 1990a) and are more extensive in the wind shadows of dunes. Trenching of niveo-aeolian deposits indicates that layers vary in thickness and may contain pure sand, pure snow, or varying concentrations of both sand and snow in mixed layers. The processes require patches of snow-free, exposed sediments for at least part of the winter, and niveo-aeolian transport and deposition are favoured by cold (semi-) arid conditions rather than snow-rich climates (Koster 1988; Koster and Dijkmans 1988). Observed dune forms and niveo-aeolian sediments indicate that the winter transport of sand is important within these dune fields (Koster and Dijkmans 1988). The transport processes can be responsible for a considerable portion of sand deposition in cold environments depending on wind and precipitation throughout the freezing season (Dijkmans 1990a).

Denivation forms develop as the snow melts, sublimates and is otherwise removed from the niveo-aeolian deposits. These features have been described in detail, especially in the early literature (Rochette and Cailleux 1971; Cailleux 1972, 1974, 1976; Ahlbrandt and Andrews 1978). The denivation forms have been examined for distinctive traces they might leave in the paleo-record which could be used to identify older and presently inactive areas of niveo-aeolian processes. Field observations and a controlled experiment to analyse the microtopography (Dijkmans and Mucher 1989) have shown that the distinctive markings disappear under the influence of aeolian processes during the summer. Even weak reworking by rainfall events can erase the traces of niveo-aeolian structures remaining from the most recent winter (McKenna Neuman 1990a).

Niveo-aeolian and aeolian sedimentation have been differentiated in two recent studies from the Quebec subarctic (Belanger and Filion 1991; Ruz and Allard 1994). The studies distinguish between sedimentation classified as *niveo-aeolian* during the winter months and *aeolian* during warmer months. Niveo-aeolian sedimentation was clearly greater than aeolian sedimentation as a percentage of the total sediment budget for surveyed transects (Belanger and Filion 1991). The percentage of niveo-aeolian transport varied as a function of the wind exposure gradient; the highest percentage occurs in open areas and the lowest in forested dune sites. Belanger and Filion (1991) affirm a previous observation (Pissart, Vincent and Edlund 1977) that sand travels further, and deposits are more dispersed, in niveo-aeolian movement. Ruz and Allard (1994) found that niveo-aeolian deposits have a coarser grain size and produce more positive skewness and higher kurtosis values. These characteristics may distinguish niveo-aeolian deposits from aeolian deposits in the sediment record. Both Quebec studies show that cold-aeolian deposition is a controlling process in the seasonal foredune dynamics of their study area. Similar results had been found on the Lake Superior shoreline where "most wind erosion and sand nourishment of the dune field take place in winter" (Marsh and Marsh 1987, 390). During the winter, the great magnitude and frequency of dry northerly winds overcome the effects of ground frost and produce surface deflation (Marsh and Marsh 1987).

Few studies have investigated the physical processes of cold-aeolian movement. A cold-laboratory study demonstrated that particle impact on hardened frozen surfaces differs substantially from transport on loose sand surfaces (McKenna Neuman 1989). The forces exerted by moving particles are large enough to fracture interparticle bonds, and collisions with the frozen surface are relatively elastic. As long as large numbers of particles do not accumulate on the surface, aeolian transport over frozen surfaces can be sustained at significantly lower wind speeds than over loose surfaces. Optimal conditions for frozen surface erosion by impact are a low surface water content (<20% by volume) and a surface temperature of approximately -22°C at which the pore ice is brittle (McKenna Neuman 1989). Subsequent experiments show that loose particle production through sublimation-drying of the frozen ground is sufficient to support or initiate cold-aeolian transport (McKenna Neuman 1990b). The rate of particle production increases as temperature approaches the freezing mark, surface pore-ice content decreases and the grains become more angular (McKenna Neuman 1990b). Field experiments emphasized wind speed and pore-ice content as the most influential variables--sediment release by pore-ice sublimation increases as the wind speed over the surface increases and as pore-ice content decreases (van Dijk and Law 1995). Substantial amounts of loosened particles become available for entrainment and transport when interstitial ice sublimates (Marsh and Marsh 1987).

2.2 Evaluation of Literature

The extent and nature of cold-aeolian processes have been made clear by a number of researchers (refer back to table 2.1), but the bulk of the literature is qualitative and emphasizes form rather than process. Many of the references to cold-aeolian phenomena are anecdotal accounts in studies which focus on other aspects of the cold region (for example, Miotke's 1984 study of slope morphology ad slope-forming processes). Sediment deposits in cold environments are described in terms of dune form and sediment stratigraphy with minimal or no reference to cold-season processes (Black 1951; Swett and Mann 1986; Dijkmans and Koster 1990). The processes are acknowledged in the study of niveo-aeolian deposits, but the sedimentological aspects are emphasized. The focus on form stems from research objectives to discover "modern periglacial analogues, where similar processes of transport and deposition occur under present-day periglacial conditions...to increase our knowledge of the paleoenvironmental conditions of relic geomorphic phenomena" (Dijkmans 1990b, 29). To date, the search for distinctly niveo-aeolian bedforms has been fruitless. The focus on the past has prevented researchers from providing much insight into "the boundary layer and surficial controls on transport and deposition" (McKenna Neuman 1993, 138). Even the Quebec studies, which give quantitative information on niveo-aeolian deposits and their importance to the annual sediment budget, make no mention of how the processes of aeolian erosion and transport differ between cold and warm environments.

Quantitative process studies on cold-aeolian movement are very few. McKenna Neuman's (1989, 1990b) cold-laboratory studies provide some much-needed information on the saltation-abrasion of frozen surfaces and the pore-ice sublimation process. Field experiments furnish evidence that laboratory studies are not sufficient for explanation by demonstrating that wind speed (a variable not measured in the cold laboratory) is extremely important (van Dijk and Law 1995). Nevertheless, *there are virtually no studies which present even simple direct measurements of aeolian transport over frozen surfaces*. The absence of such research can be partly attributed to logistical difficulties of research in cold environments during the winter season; problems include site accessibility, failure of equipment and methods under freezing conditions and the physical dangers of high winds and cold temperatures. Despite the constraints, research is badly needed to confirm existing assumptions about cold-aeolian processes and to provide quantitative data for further analysis.

Recent reviews of aeolian geomorphology either ignore cold-aeolian phenomena altogether (Sarre 1987; Chapman 1990; Sherman and Hotta 1990; Anderson, Sørenson and Willetts 1991; Nickling 1994; Livingstone and Warren 1996) or relegate it to a small mention of niveo-aeolian deposits (Pye and Tsoar 1990). The reviewers have taken little notice of the widespread occurrence of cold-climate dunes and sand sheets (Koster 1988), the areas in which cold-aeolian processes are responsible for the majority of the sediment budget (Marsh and Marsh 1987; Belanger and Filion 1991; Ruz and Allard 1994), and the effectiveness of sublimation and saltation over frozen surfaces (McKenna Neuman 1989, 1990b; van Dijk and Law 1995). A portion of the blame can be ascribed to cold-aeolian studies which "lack integration with well established aeolian transport models, research programmes and methodologies developed for warm climates" (McKenna Neuman 1993, 138). Integration with established aeolian geomorphology is especially critical as the physics of particle transport are fundamentally the same in cold regions as elsewhere. Significant differences are found only in the controls on the amount and timing of transport (McKenna Neuman 1993).

2.3 Rationale for the Current Study

The problem faced by cold-aeolian geomorphology is one of an unlikely surface on which aeolian transport is obviously taking place but with processes about which very little is known. An intriguing element in this setting is the frozen ground which appears to control the amount and timing of sediment movement. Questions centre on how wind--as the transport agent--and the frozen surface interact to produce sediment entrainment and aeolian transport. Quantitatively, investigators seek threshold conditions for entrainment and rates of transport under various wind conditions. In doing so, researchers follow an established pattern of aeolian investigation begun more than fifty years ago. The distinct cold-environment features which make traditional research patterns difficult may provide opportunities for a new approach to aeolian inquiry.

2.3.1 Measuring Thresholds and Transport Rates

Historically, aeolian researchers have defined threshold friction velocities (u_{*t}) and particle transport rates (q) by measuring entrainment and transport in wind tunnels and using field studies, theory and simulations to flesh out the results (see appendix A for a list of symbols). Wind tunnels allow researchers to control surface and wind characteristics and thereby investigate a wide range of conditions. Field studies confirm wind tunnel measurements, and theoretical calculations and computer simulations further explore the processes. The pattern of investigation began with Bagnold's research in 1941 which gave original equations for u_{*t} and q based on wind tunnel results, field measurements in the Libyan desert and physical principles. Many subsequent researchers went to their wind tunnels to modify Bagnold's equations or produce alternate ones (for example, Zingg 1953; Kawamura 1964; Kadib 1964; Hsu 1973; Lettau and Lettau 1978; White

variables	studies
sediment shape and density	Willetts, Rice and Swaine 1982; Willetts 1983; Rice 1991
roughness elements and vegetation	Chepil 1950; Logie 1982; Janin 1987; van de Ven, Fryrear and Spaan 1989; Iversen *et al.* 1990; Musick, Trujillo and Truman 1996
bedslope	Rasmussen *et al.* 1996; Wiggs, Livingstone and Warren 1996
soluble salts and crusting	Nickling and Ecclestone 1981; Nickling 1984; Rice, Willetts and McKewan 1996
moisture content	Belly 1964; Logie 1982; McKenna Neuman and Nickling 1989; van Dijk *et al.* 1996

Table 2.2 Research on aeolian variables using wind tunnels

1979). Wind tunnels were also used to investigate how aeolian activity is influenced by sediment shape and density, roughness elements and vegetation, bedslope, soluble salts and crusting, and moisture content (table 2.2).

The pattern of research suggests that aeolian activity on frozen surfaces should also be examined by wind-tunnel experiments. Controlled experiments in which varying wind speeds are passed over frozen soils with specific water contents could define thresholds for movement on frozen surfaces. Similar experiments measuring fully-developed transport rates could define relationships between frozen surface controls and rates of movement.

Studying a frozen surface in a wind tunnel presents much greater challenges than studying a non-frozen surface. Initial difficulties pertain to research facilities. Valid experiments, in which temperature gradients between the frozen surface and its surroundings are prevented or controlled by design, require that the wind tunnel be located in a temperature-controlled chamber. Such facilities are understandably expensive to construct, and there are very few in existence. Optimally, the research facilities should also permit control of humidity because this variable influences surface drying. When appropriate facilities have been located, research difficulties centre on experimental set-up. Temperature, humidity and wind speed can be appropriately controlled, but soil water content is more challenging. The natural tendency of the soil is to dry out, and this tendency is enhanced when wind is blown over the surface. Any experiment to determine a threshold wind velocity for a specific water content faces a dilemma: as strong winds are blown over the surface, the water content becomes increasingly lower than initially specified. Surface drying of wet surfaces in wind tunnel experiments was overcome by using capillary action to draw water up through the soil (Belly 1964); the same option is not available for frozen surfaces. Pre- and post- experiment measurements pore-ice content may not be similar to water contents of transported sediments when frozen surfaces are exposed to wind.

Assuming a temperature- and humidity- controlled chamber surrounding a fully-working wind tunnel is available and a frozen surface can be prevented from drying, there is no guarantee that the sand will actually move. It is possible and even probable that a wind tunnel cannot produce winds strong enough to detach grains from the frozen surface. Logie (1982) noted that a wind tunnel could not produce velocities high enough to entrain sediments from saturated unfrozen sands; Svasek and Terwindt (1974) noticed the same effect on a natural beach. Frozen sand has stronger cohesion in the pore ice than wet sand does in the liquid water. In the field, researchers have observed that sand grains cannot be entrained until the surface is first dried by sublimation (Marsh and Marsh 1987). Between the extremes of uncemented and cemented frozen sands, there is probably a range of low water contents at which wind forces can overcome weak ice bonds, but this range may be quite small.

An alternate wind-tunnel experiment would be to expose frozen surfaces to specific wind speeds and measure times to entrainment. Belly (1964) and Logie (1982) set the precedent for experiments of this kind when they measured times to entrainment for wet surfaces. By varying wind speeds, temperatures, humidity and initial water content, one could produce a fairly complete picture of entrainment from frozen surfaces. The caveat to this method is that it no longer measures instantaneous thresholds for entrainment. In fact, the results reflect pore-ice sublimation under various conditions and are the wind tunnel equivalent of sublimation experiments in the field (van Dijk and Law 1995) and laboratory (McKenna Neuman 1990b). There is a need for experiments of this kind where conditions can be controlled and varied, but they are inherently different than, for example, Bagnold's (1941) or Nickling's (1988) wind tunnel experiments.

2.3.2 New Opportunities in Cold Environments

The traits that make frozen-ground wind-tunnel studies so challenging open new avenues for research when they are viewed from a different angle. Frozen-surface drying generates all sorts of complications in experiments designed to measure wind thresholds and transport rates. When the focus of research becomes frozen-surface drying, a valuable side-effect is the quantification of entrainment and transport rates. The change is *from* measuring processes in which there are some restrictions on supply *to* measuring constraints and sediment supply as a means of quantifying the subsequent processes.

The significant effects of sediment supply on aeolian processes has merited attention in many recent publications. A common theme is that predicted transport amounts differ widely from measured amounts in coastal and humid areas where (quasi-) ideal surfaces do not exist (Sarre 1989; Pye and Tsoar 1990; Sherman and Hotta 1990; Gomes, Andrade and Romariz 1992; Kocurek *et al.* 1992; Nordstrom and Jackson 1992). The differences between potential and actual movement do not result from the diminished competence of the wind; rather they stem from constraints on sediment supply including wind speeds too close to thresholds of movement, vegetation, high water table, pebble-lag formation, high moisture levels, steep beach slopes, differences in air density, and presence of binding salts (Nordstrom and Jackson 1992, 776). Winds with the potential to move sand exceed sediment supply at many sites (Nordstrom, Carter and Psuty 1990), and sand transport equations provide only estimates of maximum rates of sand movement (Pye and Tsoar 1990, 119). In fact, Sarre (1989, 257) insists that a comparison between actual transport and potential transport clearly shows the inability of the latter to provide a fair estimate of sand movement from temperate beaches. In some cases, a shift in focus may be necessary as

> there is a likelihood that for a large proportion of the time in coastal dune settings...the problem is not a matter of defining the functional dependence of the mass flux on the wind speed, but rather the rate of sediment *supply* from a wetted bed to the wind, which will involve the thermodynamics of evaporation more than the fluid and solid mechanics of saltation (Anderson 1989, 164).

Researchers must investigate how much sediment the surface can supply instead of how much sediment the wind can erode and transport.

Constraints to sediment supply for aeolian processes in cold environments are equal if not greater than constraints imposed by coastal or humid areas. In cold regions, restrictions to sediment supply include pebble-lag surfaces, snow cover, surface ice and ground freezing. The role of ground freezing is similar to non-frozen moisture in that drying is an essential part of releasing sediments to aeolian processes. The inherently supply-limited nature of cold environments suggests that they may be good candidates for a research approach which studies supply mechanisms to form realistic predictions of sand movement.

2.4 Research Assumptions and Boundaries

This study adopts a supply-limited approach in its quantitative investigation of cold-aeolian processes. The approach accounts for the real constraints of the cold environment and allows factors such as pebble-lag development, snow cover, surface ice and ground freezing to be incorporated into the discussion. Credible predictions of sand movement result from investigating how the rate of sediment supply governs the rate of sediment transport.

The assumptions of a supply-limited approach to cold-aeolian movement should be made clear at the outset. The primary assumption is that sediment for aeolian processes is restricted by ground freezing and supplied by pore-ice sublimation. It follows that if the amount of sediment released by pore-ice sublimation is known, the amount of sediment available for transport is known. Actual transport takes place when wind velocities exceed the threshold for the grain-size, as calculated for loose sand. In areas where wind often exceeds the threshold, one can assume that all of the sand released from the frozen surface will eventually be removed by the wind.

Two aeolian mechanisms fall outside the boundaries of the supply-limited approach. The first is the ability of some wind speeds in excess of the threshold velocity for loose sand to break weak ice bonds at low surface water contents. The second is the ability of moving particles to abrade downwind frozen surfaces and release additional particles through surface impacts. Limited time and resources place both of these processes outside the scope of the current investigation into supply-limited cold-aeolian activity. Both fluid entrainment and abrasion in cold regions should be the focus of future cold-aeolian research.

2.5 Summary

Aeolian phenomena, occurring when sediment and boundary layer temperatures are below freezing, have been observed in middle- and high- latitudes, seasonally- and perennially-cold regions, and on coastal and inland sediments. Attention has been devoted to niveo-aeolian deposition and denivation forms in a search for distinctive traces of cold-aeolian activity in the paleo-record. In the immediate past, niveo-aeolian sedimentation has made significant contributions to the annual sediment budget near Hudson Bay and Lake Superior. Process investigations have been limited to two cold-laboratory studies and a single field study. A critical review of the literature indicates that cold-aeolian research is largely qualitative, emphasizes form and pays little attention to processes, and remains on the periphery of mainstream geomorphology.

There are two ways in which the necessary quantitative research into cold-aeolian processes can be carried out. The traditional pattern of aeolian research focuses on the wind's ability to entrain and transport sediments through wind-tunnel studies on specific surfaces. Such experiments are difficult in the face of expensive facilities, the complexities of producing and measuring a bed of frozen sediments, and the real possibility that frozen sediments cannot be directly entrained. Recent attention in aeolian geomorphology has been given to supply-limitations inherent to complex environments and especially humid coastal beaches and dunes. A focus on measuring environmental constraints and supply mechanisms has real potential in cold regions where there are distinct limits to sediment supply. This study adopts a supply-limited approach to studying cold-aeolian activity.

Chapter Three

REVIEW OF SUPPLY LIMITATIONS AND COLD ENVIRONMENTS

Our knowledge is a receding mirage in an expanding desert of ignorance.
Will Durant

The first step in applying a supply-limited approach to cold-aeolian activity is an assessment of available information on sediment supply. The review of information necessarily focuses on initiation of movement because this is the stage where many of the restrictions--and the mechanisms to overcome restrictions--are active. A useful starting point is the classical aeolian problem of sediment movement on an ideal surface. On this foundation, aeolian geomorphologists have based discussions of limiting factors in warm environments. Very few details are available with respect to cold environments. Research on ground freezing and pore-ice cementation, drawn from engineering and physics, are applied to aeolian processes. Pore-ice sublimation is the mechanism for particle release; both ground freezing and pore-ice sublimation function as the dominant controls on sediment supply in cold environments. Less information is available about other factors such as snow and surface ice. Ultimately cold-aeolian activity is a complex combination of conditions and effects, restrictions and supply. As the breadth of the current information unfolds, it becomes apparent that many areas need further attention before there can be a good understanding of cold-aeolian processes.

3.1 Back to the Basics: the Ideal Surface and Entrainment

The initial movement of a single sand particle from a position at rest can be described in terms of the forces acting on the grain (figure 3.1). Wind flowing over the grain exerts a horizontal drag force and a vertical lift force. These forces are opposed by inertial forces of which the grain's weight acting directly opposite the lift force is the most important (Pye and Tsoar 1990). The appropriate parameter is the submersed particle weight

$$W = C_s(\sigma - \rho)gd^3 \tag{3.1}$$

where σ is the density of the particle, ρ is the density of the fluid above the particle, d is the particle diameter and C_s is a shape coefficient equal to $\pi/6$ for a sphere (Iversen *et al.* 1987; Pye and Tsoar 1990). Cohesive forces (including van der Waals forces and electrostatic charges) must also be taken into account for fine grains. At the moment of entrainment, the fluid drag (F_d) and lift (F_L) forces are just able to overcome the resistance of the weight (W) and any cohesive forces. Just prior to movement, a balance of the forces can be obtained by summing the moments around the pivot point P:

$$F_d a + F_L b = Wb \tag{3.2}$$

where a = (d/2)cosφ and b = (d/2)sinφ are the moment arms (Pye and Tsoar 1990). With a slight increase in the fluid velocity, the particle will rotate about point P and possibly lift from the surface.

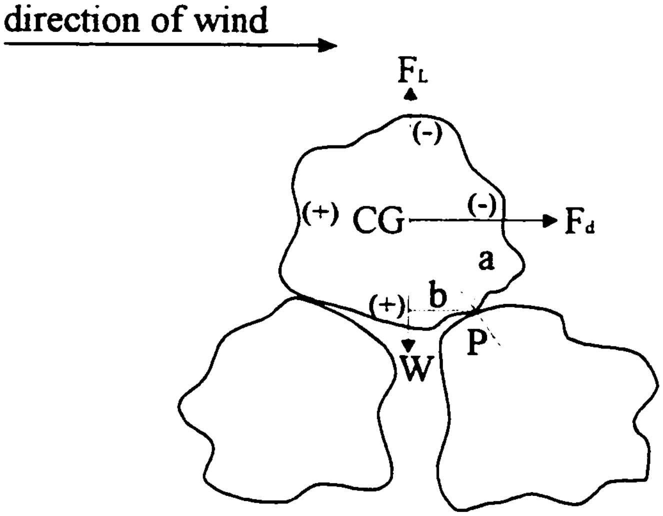


Figure 3.1 Forces acting on a grain (with centre of gravity CG) in a wind flow (modified from Pye and Tsoar 1990); relatively high (+) and low (-) pressure areas surface are indicated

The total drag force (F_d) is a combination of the pressure drag (a positive velocity pressure acting against the windward side of the grain) and the skin friction drag (a negative viscosity pressure on the lee side of the grain). The drag force on a sphere is

$$F_d = \beta \rho u_*^2 \left(\frac{\pi d^2}{4}\right) \tag{3.3}$$

where $(\pi d^2)/4$ is the grain's largest projected area, ρu_*^2 is the surface shear stress and ß is a coefficient based on the relative position of the grain in the bed, turbulence and the height of drag force action (Pye and Tsoar 1990). Because the drag force imparts forward momentum to the particle, early reports suggested that initial grain motion was solely due to the drag forces. This assessment was coupled with observations that grains begin to move by rolling along the surface until they gain sufficient speed to be thrown into saltation (Bagnold 1941; Chepil 1945).

Subsequent studies have shown that a lift force is essential to the initial movement of a particle. The dynamic lift force is caused by the Bernoulli effect which produces a negative static pressure on the top of the grain. The lift force is necessary to pull the grain away from the surface and into the flow (Einstein and El-Samni 1949). The average lift force on a sphere in a fluid is

$$F_L = \Delta p \frac{\pi d^2}{4} = \left(C_L \rho u^2 \frac{\pi d^2}{4}\right)/2 \tag{3.4}$$

where Δp is the pressure difference between the top and bottom of the sphere, $\pi d^2/4$ is the grain's largest projected area, C_L is the coefficient of lift and u is the fluid velocity measured 0.35d above the theoretical surface represented by the roughness length, z_0 (Pye and Tsoar 1990). The ratio F_L/F_d is constant for a range of roughness element sizes and friction velocities; this ratio was first reported as 0.85 and later modified to 0.75 (Chepil 1959, 1965). More recently, it has been reported that drag and lift forces appear to be of the same magnitude for relatively high Reynold's numbers (Nickling 1994). The importance of a lift force in initial movement has been affirmed by observations that grains are ejected into the air after vibrating, and not after rolling along the surface (Bisal and Nielsen 1962; Lyles and Woodruff 1972). In fact, the large density differences between the air and the grains make rolling unlikely and initial grain movement is consistent with the instantaneous air pressure difference of a lift force (Nickling 1988).

The shear velocity of wind required to initiate the movement of sand of a predominant diameter is the fluid threshold (Bagnold 1941). The shear (or drag) velocity (u_*) is the amount of shear stress (τ) the wind experiences parallel to the direction of flow. As a measure of the velocity gradient of the wind, the shear velocity can be obtained from wind profile measurements or determined with the following equation relating shear stress and air density:

$$u_* = \sqrt{\frac{\tau}{\rho}} \tag{3.5}$$

Equations for critical shear stress (τ_c), which is the minimum shear stress needed to initiate movement from the surface, have been suggested by Chepil (1959) and others based on many characteristics of exposed grains such as grain packing, angle of repose, etc. To date, the most widely used and often quoted calculation of fluid threshold shear velocity (u_{*t}) is Bagnold's (1941) equation

$$u_{*c} = A\sqrt{\left(\frac{\sigma-\rho}{\rho}\right) gd} \tag{3.6}$$

where A is a dimensionless coefficient empirically observed by Bagnold to be 0.1. Subsequently, it has been shown that the value of A could range from 0.1 (Zingg 1953) to as high as 0.2 (Lyles and Woodruff 1972). A dimensionless form of the threshold shear velocity equation has been proposed by Iversen *et al.* (1987):

$$A_n = \frac{A}{\sqrt{\frac{1+0.055}{(\sigma-\rho)\,gd^2}}} \tag{3.7}$$

where A_n is the dimensionless threshold velocity and A^2 is the dimensionless shear stress.

Equation 3.6 retains a greater popularity and is the basis for many equations pertaining to specific surfaces. Recent evaluations indicate that it provides a reasonable prediction of the critical shear velocity for grain-sizes between 0.1 and 2.0 mm diameter (Hotta 1988; McKenna Neuman and Nickling 1989; Sherman and Hotta 1990).

Particle size is very important to fluid entrainment; so much so that Chepil (1945) insists size is the greatest single factor influencing the threshold velocity. Equation 3.6 has the threshold shear velocity increasing linearly with the square root of grain diameter (figure 3.2). It is important to note that this threshold law does not apply to grain sizes below

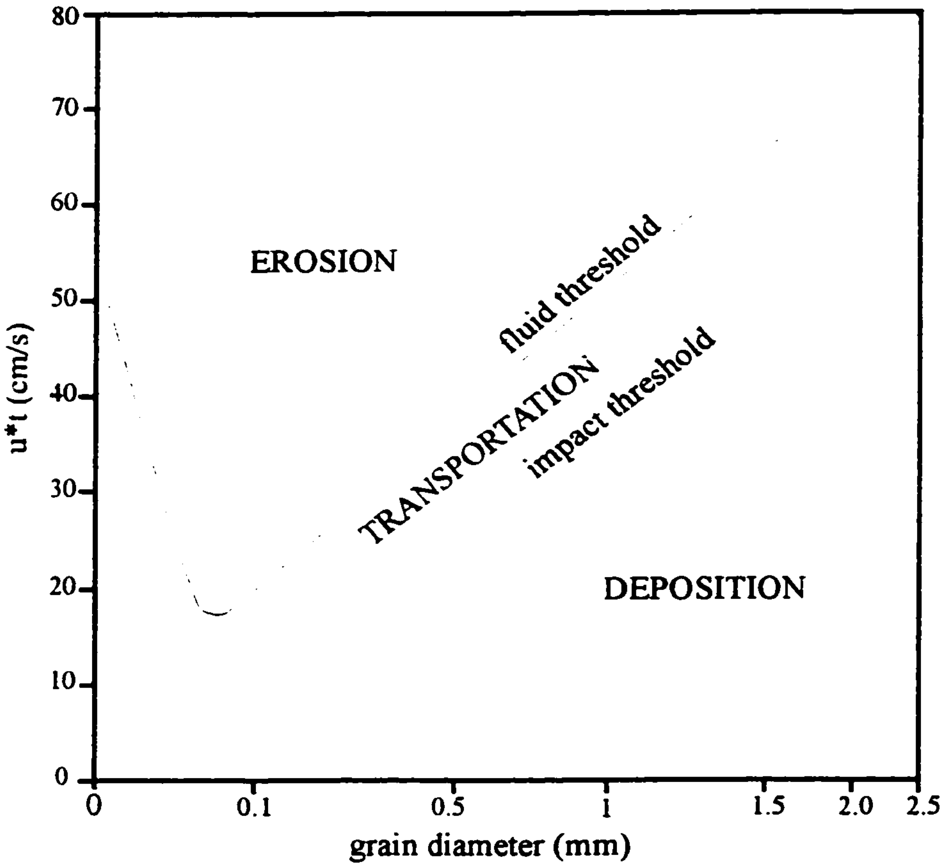


Figure 3.2 Variation in threshold velocity with grain size (from Pye and Tsoar 1990, 94); the impact threshold is approximately 80% of the fluid threshold

0.1 mm (Chepil 1945; or 80 μm according to Nickling 1994). Grains with diameters larger than 0.1 mm protrude into the air stream and bear a greater proportion of the fluid drag than the general surface (Nickling 1994). Smaller grain sizes ($d > 0.1$ mm) do not act as individual roughness elements projecting into the air, and the surface is aerodynamically smooth (Sarre 1987). The value of coefficient A rises rapidly as the drag is distributed over the entire surface instead of a few isolated grains (Nickling 1994). Interparticle forces, such as electrostatic charges and van der Waals forces, also become very important for fine grains (Pye and Tsoar 1990; Nickling 1994).

Generalized forms of the threshold velocity equation have been developed to explain the entire size range. A good review of these equations can be found in Nickling (1994). They are not addressed here because Bagnold's equation (3.6) is considered a good approximation for sand-sized particles. Its simplicity is preferred over the complex equations which cover the entire size-threshold curve. In addition, Bagnold's equation is used in discussions of various restrictions on sand movement.

3.2 Adding Layers: Complex Surfaces and Entrainment

The ideal surface--horizontal, dry, unobstructed and unvegetated (Sherman and Hotta 1990, 20)--exists mainly in wind tunnels or warm arid deserts and bears little resemblance to the beaches, dunes and sand sheets found in coastal or humid environments. Most natural surfaces are influenced by factors which either modify the wind flow over the surface or increase the resistance of surface grains to movement. To further complicate matters, aeolian processes in humid and coastal environments can encounter multiple restrictions.

Variables which modify wind flow over a surface include bedslope, surface roughness, and vegetation. Bedslope influences ripple form, saltation, and collision (Willetts and Rice 1989; Anderson, Sørenson and Willetts 1991), but it is less well-known that the threshold of movement is raised on positive gradients and lowered on negative gradients (Pye and Tsoar 1990). When roughness elements are present, entrainment depends on the height and number of non-erodible elements exposed to the wind (Bagnold 1941; Chepil 1950; Iversen *et al.* 1990). Local flow acceleration promotes scouring below a critical cover density called an inversion point (Pye and Tsoar 1990), whereas greater heights and/or higher densities of roughness elements raise the threshold shear velocity and shelter the remaining erodible grains (Borowka 1980; Greeley and Iversen 1985). Vegetation is a unique form of surface roughness in that it is generally porous, semi-compliant, and able to regenerate surface roughness by putting out new growth after being partially buried (Olsen 1958; Maun 1997). Size and spacing are important and the effect of vegetation changes from accelerated erosion to protection at a critical cover density (Bressolier and Thomas 1977; Willetts 1989). Estimates indicate that little or no sand movement will take place when vegetation cover exceeds 30% of an area (van de Ven 1989; Pye and Tsoar 1990).

Biological and physical factors increase the resistance of surface grains to movement. Biologically, algae and cyanobacteria stabilize a surface by aggregating sand grains and causing them to resist entrainment by wind (Booth 1941; Bond and Harris 1964; van den Ancker, Jungerius and Mur 1985; Jungerius and vander Meulen 1988; Yair 1990; Maxwell and McKenna Neuman 1994). In terms of physical interactions, van der Waals forces, electrostatic charges and forces between adsorbed films on grains are responsible for the increase in threshold velocities needed to entrain particles with less than 0.1 mm diameter (Sarre 1987; refer back to figure 3.2). For larger grains, cohesive forces result from soluble salts and moisture. Even small amounts of soluble salts produce cement-like bonds which hold individual grains in place (Nickling and Ecclestone 1981; Nickling 1984). Moisture cohesion also binds sand grains together, but not to the same extent.

3.2.1 Case Study: (Liquid) Moisture and Sand Movement

In humid and coastal aeolian environments, liquid moisture has a widespread effect on sand movement. Like other forms of cohesion, interstitial water binds sand grains together and increases their resistance to entrainment. Unlike most other forms of cohesion, moisture cohesion is ephemeral and decreases, even disappears, as the liquid water evaporates. This complicates the discussion of moisture and entrainment.

The ability of surface moisture to limit aeolian processes increases as the moisture content of the sand surface layer increases. When the moisture content is small, sand transport is comparable to that on a dry surface (Azizov 1977; Hotta 1988; Sarre 1988). As the moisture content increases, the threshold shear velocity also increases. Most studies have determined that this increase is exponential (Chepil 1956; Belly 1964; Azizov 1977) although Hotta (1988) counters that the increase is linear up to 10% moisture. Some of the studies also refer to critical and limiting moisture contents (figure 3.3). The critical moisture content is the value below which the moisture has an insignificant effect on the threshold velocity and above which there are considerable decreases in the aeolian transport rate (Azizov 1977; Hotta 1988). The limiting moisture content is the value above which no or very little movement will take place; above this moisture content, threshold shear velocities are largely theoretical as such wind speeds rarely occur naturally. Differences in assessing critical and limiting moisture contents can be attributed to the diverse sediments and the variety of methods used by researchers. For sand it appears that very little movement takes place when the surface moisture content exceeds approximately 4%, whereas under approximately 1%, the moisture content has little effect on the surface resistance to the wind (Belly 1964).

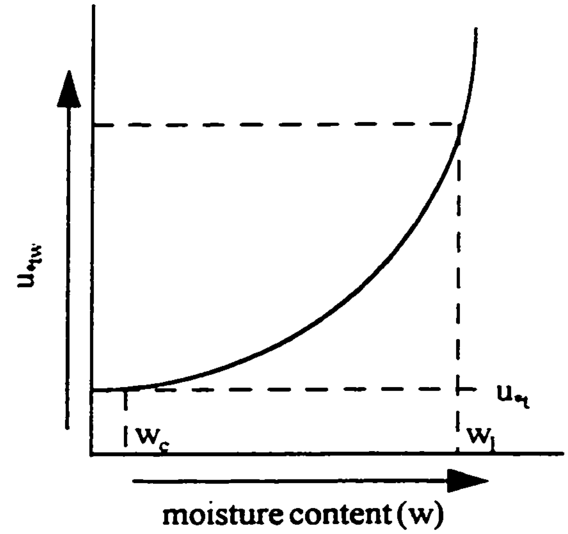


Figure 3.3 Relationship between surface moisture content and threshold shear velocity. Critical (w_c) and limiting (w_l) moisture contents are indicated.

A modified equation 3.6 describes the new threshold shear velocity for wet surfaces (u_{*tw}) because moisture content directly influences threshold shear velocity (Bisal and Nielsen 1962; Johnson 1965; Bisal and Hsieh 1966; Svasek and Terwindt 1974; Hotta 1988; McKenna Neuman and Nickling 1989). Studies from coastal areas, where moist sand is common, still quote the threshold equation from Belly's (1964) wind tunnel study:

$$u_{*tw} = A\sqrt{\frac{\sigma-\rho}{\rho}gd}\,(1.8+0.6\log_{10}w) \qquad (3.8)$$

where the moisture content (w) has a range of 0 to 4%. However, equation 3.8 (along with two other Japanese equations) was rejected by Hotta (1988) after his examinations indicated that its predictions were not accurate. Hotta (1988) formulated the equation:

$$u_{*tw}=A\sqrt{\frac{\sigma-\rho}{\rho}gd}+7.5w \qquad (3.9)$$

for grain sizes (d) of 0.2 to 0.8 mm and moisture contents of less than 8%; the constant 7.5 has dimensions of (cm/s)/%. Equation 3.8 also consistently over-predicts thresholds observed by McKenna Neuman and Nickling (1989). These authors claim that water tension (which is independent of particle size) is a more appropriate parameter for threshold shear velocity than moisture content. By recalculating the forces acting on the grain to include the capillary forces (F_c), they found that

$$u_{*tw} = A\sqrt{\frac{\sigma-\rho}{\rho}}\,[\frac{6\sin 2\beta}{\pi d^{3}(\sigma-\rho)\,g\sin\beta}F_{c}+1]^{1/2} \qquad (3.10)$$

where ß is the particle resting angle (McKenna Neuman and Nickling 1989, 82). McKenna Neuman and Nickling approximate natural grain contacts by cones (figure 3.4), and the capillary force (F_c) between the symmetric cones touching at their apices is defined by

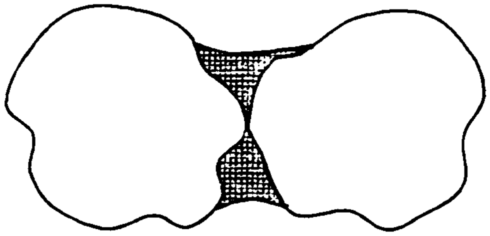


Figure 3.4 Wedge of water surrounding the contact point of two sand grains (after McKenna Neuman and Nickling 1989)

$$F_c = \frac{\pi T^2}{P} G \qquad (3.11)$$

where T is the surface tension of the water, P is the pressure deficiency and G is related to the geometric properties of the contacts (McKenna Neuman and Nickling 1989, 81). While equation 3.8 appears to be limited to the sediments and conditions under which it was produced, equations 3.9 and 3.10 have not yet been compared to assess which equation would better describe observed data. Despite the strong theoretical basis of equation 3.10, the additional information necessary for the calculations may offset improvements in prediction over equation 3.9 and its single variable of moisture content.

Sand movement on wet surfaces is complicated by the ephemeral nature of moisture and the variability of surface moisture content over time. When an unsaturated wind blows over wet sand, it gradually dries the surface and decrease the soil's resistance to wind action (Johnson 1965; Bisal and Hsieh 1966). Equations which do not consider the evaporation rate overestimate the protective nature of soil moisture (Logie 1982). Hotta (1988) suggests the following equation

$$u_{*tw} = A\sqrt{\frac{\sigma - \rho}{\rho} gd + 7.5 w I_w} \qquad (3.12)$$

where I_w takes on values of 0 to 1 depending on the evaporation rate; when the wind's shear velocity exceeds u_{*tw}, $I_w = 1$ and equation 3.9 is formed. The evaporation of moisture need only take place in the topmost grain layer; dry surface grains can move even when the sand millimetres below the surface is still very wet (Svasek and Terwindt 1974). Correspondingly, the reduction of surface moisture will only take place when the capillary rise of water is slower than evaporation (Svasek and Terwindt 1974; Nickling and Ecclestone 1981). Deflation of surface grains can halt sand movement by exposing the wetter underlying grains.

Surface moisture produces spatial and temporal variations in sand movement. Moisture content often varies spatially, and evaporative drying can also differ from place to place. Sand transport begins on local areas of drier material (Logie 1982). After initiation, downwind areas, even with higher moisture contents, will undergo sand transport as the impact of saltating grains overcomes the capillary forces (Svasek and Terwindt 1974). As the process continues,

> water adhering to sand grains once dislodged from the wet sand surface quickly evaporates as the grains are blown off to the downstream. When the dislodged sand grains again fall to the sand surface, the grains give momentum (or energy) to the sand surface. Therefore, blown sand generated from areas of impact would be greater than that in areas located upstream. The result is that if there is a considerable travel distance at the upstream, the sand transport rate passing a fixed section will be the same as that on the dry sand surface even though the sand surface is wet. (Horikawa *et al.* 1984, 225).

Sediment does not always move continuously, even when the threshold velocity is exceeded. Deflation can expose moist sediments which are less mobile than drier surface sediments (Nordstrom and Jackson 1992). Movement will slow down or stop until the surface dries out enough to permit movement once again.

3.3 New Directions: Cold Environments

In cold environments, other influences on aeolian activity become evident. The predominant element is ground freezing in which soil moisture cements sand grains together. Just as liquid moisture evaporates and allows sand grains to move once again, frozen moisture sublimates and enables the wind to entrain surface sediments. The following sections on ground freezing, pore-ice cementation and particle release by sublimation are deliberately thorough because they involve relatively new concepts to aeolian geomorphology. Additional variables which influence aeolian activity in cold environments are discussed more briefly.

3.3.1 Ground Freezing

Ground freezing begins when the soil temperature drops below 0°C. The ground cools from the top down as heat is lost to the atmosphere through conduction and convection. Pore water freezes at temperatures below 0°C, with the exact freezing point depending on how tightly the water is bound to the soil particles. In pure sands, the loosely-bound pore water freezes at temperatures very close to 0°C, whereas the hygroscopic water in finer soils can remain liquid well below -5°C (Williams and Smith 1989, 7). In all soils the freezing process involves some supercooling which is usually unstable (Williams and Smith 1989, 179). When the pore water reaches the depressed freezing point, stable ice crystals form abruptly in a process of nucleation. Researchers have suggested the nuclei are soil particulates (Anderson, Pusch and Penner 1978), aggregations of water molecules (Andersland and Ladanyi 1994, 27), or even the liquid-air interface during rapid coolings (Colbeck 1982, 120). Whatever the nuclei, each nucleation produces a circular ice embryo which is metastable at slightly below 0°C (Miller 1973; Colbeck 1982, 118). The process also releases latent heat (roughly 334 J g^{-1}) which causes the temperature of the immediate area to rise slightly (Andersland and Ladanyi 1994, 24).

As the soil temperature drops further, the metastable ice embryos grow into crystals within the pore spaces. Anderson, Pusch and Penner (1978, 75) suggest that the crystals are not attached to the mineral grains and they grow until they interfere with one another. Crystal shape is at least partially dictated by the soil particles, and multicrystalline aggregates form as crystals grow into the liquid or free water (Colbeck 1982, 118). As the crystals seek out a configuration of minimum surface area, they form grain boundaries (Anderson, Pusch and Penner 1978, 75). In an alternate explanation, Razbegin (1989, 420) suggests that the pore spaces fill irreversibly with ice in an instantaneous jump when the free water freezes.

The freezing front moves down through the soil as the temperature of the soil continues to decrease. If the soil is not saturated with water, some pore spaces will fill at the expense of others (Colbeck 1982). Colbeck suggests that small pores will fill before larger ones during rapid freezing, but the reverse may be true at other times. Some soils experience migration of moisture towards the freezing front; the moisture movement adds ice to the pore spaces even to the point of creating ice-rich zones or ice features within the soil. The moisture migration and related phenomena (ice inclusions, frost heaving) are limited to predominantly fine-grained soils and not found in sand with its larger grains. Tsytovich (1975, 55) claims that the moisture content decreases towards the freezing front in medium-grade sand. When free drainage exists in at least one direction, water is squeezed out during freezing and the porosity of a saturated sand does not change (Tsytovich 1975, 55).

3.3.2 Description of Frozen Soils

A frozen soil has very different mechanical and thermophysical properties than an unfrozen one. The changes in soil characteristics stem from distinctive properties of pore ice and interactions between the frozen soil components. Frozen soil (figure 3.5) contains solid mineral particles, ice, liquid water, water vapour, and possibly other materials such as salts and organic material. The solid mineral particles make up the soil skeleton and delineate the pore spaces. Ice is found within the pores and, as the most influential component of the frozen soil, is responsible for cementing the mineral particles together and changing the thermal conductivity, heat capacity and other soil properties. Unfrozen water is found in a thin, tightly-bound layer around the mineral particles. In fine-grained soils, the unfrozen water aids moisture migration and leads to

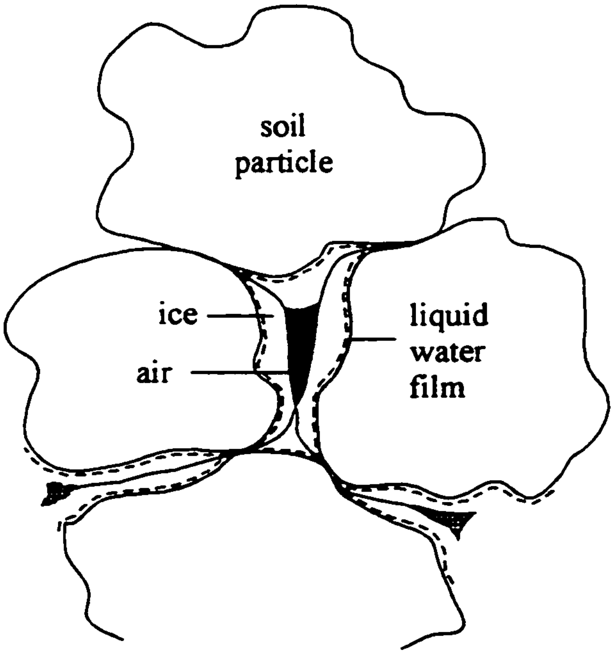


Figure 3.5 Structural elements of frozen soil (after Williams and Smith 1989)

frost heaving, but in sands the unfrozen water is minuscule. If the soil is not saturated, air is also present within the pores. The air allows water vapour to move through the frozen soil and enhances pore-ice sublimation. The presence of other materials may also modify soil properties (for example, dissolved salts can depress the freezing point of water; Williams and Smith 1989, 174; Andersland and Ladanyi 1994, 23).

The most influential component of the frozen soil is ice. At temperatures between 0°C and -100°C and under standard pressure, pore ice is ordinary crystalline ice (class I; according to Tsytovich 1975, 24; Anderson, Pusch and Penner 1978, 73). In its solid state, the constituent atoms of water are arranged in a crystalline lattice--a fairly rigid three-dimensional array (Halliday, Resnick and Walker 1997, 350). The lattice has a hexagonal system and ice exhibits considerable property anistropy (it has different physical properties in different directions). In frozen soils, the pore ice is polycrystalline and randomly oriented; its properties may therefore appear isotropic (Andersland and Ladanyi 1994, 121). A special structural property of ice is the mobility of hydrogen atoms in the crystal lattice; this mobility decreases under lower temperatures (Tsytovich 1975, 24). The rigid crystalline lattice enables ice to cement soil particles into a cohesive mass. Because hydrogen atoms lose their mobility under decreasing temperatures, ice is stronger and able to bind particles more firmly at lower temperatures. When water changes to ice, its thermal properties change also; thermal conductivity increases four-fold and heat capacity decreases by half (Williams and Smith 1989, 87).

3.3.3 Pore-Ice Cementation and Aeolian Entrainment

With respect to sand movement by wind, the cementation of soil particles is the most interesting attribute of pore ice. The ice acts as a matrix or internal bonding agent within the soil (Phukan 1985, 56) and cements sand grains which have no cohesion on their own. In doing so, pore ice has been compared to the calcite in calcareous sandstone (Tsytovich 1975, 21) and the Portland cement in building concrete. Both comparisons are apt, highlighting the strength of the resulting material and the increased resistance of the cemented mineral particles to movement of any kind. For frozen sands, pore ice cementation means an immediate and substantial increase in sand grain resistance to entrainment and movement by wind.

The ice-cement bonds hold minerals in place by means of a rigid crystal lattice. Although the ice is not in direct contact with the mineral grains, the intervening thin film of liquid water is so tightly bound to the mineral surface by intermolecular forces that it does not lessen cementation. Ice-to-grain contact area affects the strength of ice-bonding (McKenna Neuman 1990b, 333); therefore soil water content and grain shape influence the degree of cementation. For discussion purposes, the thin film of liquid water is viewed as an extension of the grain. The fixed water is so strongly attached to soil particles that it moves and deforms with them (Frémond and Mikkola 1991, 17).

The ice-cement bonds are responsible for strength and deformation properties of the frozen soil and have a pronounced time-dependent behaviour (Tsytovich, 1975; Phukan, 1985; Williams and Smith, 1989). Under large or quick stresses, the ice bonds in the frozen sand behave elastically and failure is brittle when it occurs (Williams and Smith 1989, 240). If lower levels of stress are applied for longer time periods, the ice-bonds show ductile yielding; in other words, they have no long-term strength and will deform and flow under small loads (Anderson, Pusch and Penner 1978, 254).

The degree of cementation in a frozen soil depends on the amount of ice present and its temperature. In frozen soil descriptions, cementation has been rather broadly assigned to two categories: 1) *poorly-bonded* in which the soil is weakly held together by ice and has poor resistance to chipping and breaking, and 2) *well-bonded* in which the soil is strongly held together and has a relatively high resistance to chipping and breaking (ASTM 4083-89 1994, 487). Ice-bond strength and cementation tend to increase as ice temperature, and hydrogen mobility, decrease. At the same time, ice-to-grain contacts and cementation increase as soil water content increases. The relationship between water content and cementation is broadly outlined in table 3.1. The classifications do not refer to

water content	cementation	description
none	none	loose material
low	friable	material easily broken under light to moderate pressure (ASTM 4083-89 1994, 486)
	poorly-bonded	weakly held together by ice and has poor resistance to chipping or breaking (ASTM 4083-89 1994, 487)
high (up to saturation)	well-bonded	strongly held together by ice and has a relatively high resistance to chipping or breaking (ASTM 4083-89 1994, 487)
oversaturated	ice-rich	decreasing amount of grain-to-grain contacts (ie, beginning to be soil in ice instead of ice in soil); frozen soil strength decreases

Table 3.1 Water content and frozen ground cementation

specific water contents because engineers have been more interested in long-term bearing capacity which is not influenced by moisture content until oversaturation.

Cold-aeolian research is more concerned with the first three categories in table 3.1. Cementation governs the resistance of surface grains to movement by wind (table 3.2). Thus, sediment resistance to movement is highly dependent on the temperature and water content of the frozen surface. Specific values for water contents bounding each category are desperately needed, as are clarifications of the wind's ability to fluidly entrain particles from each category. Given the slim range of moisture contents from which fluid entrainment of wet sand is possible, it is likely that fluid entrainment from frozen sands takes place from a more restricted range.

water content	cementation	aeolian entrainment
none	none	loose surface; no change to entrainment
low	friable/poorly-bonded	threshold shear velocity increases; it may not be possible for natural winds to reach the higher thresholds
high (up to saturation)	well-bonded	particles too strongly bound for fluid entrainment; pore-ice sublimation is required before entrainment
oversaturated	ice-rich	particles too strongly bound for fluid entrainment; pore-ice sublimation is required before entrainment

Table 3.2 Frozen-ground cementation and aeolian entrainment

Saltating grains apply rapid stresses in each of their impacts with the frozen surface. The interstitial ice can be expected to behave elastically with brittle failure occurring if the impact forces are great enough. If individual impacts are not enough, successive impacts may detach sand grains from the surface. No data are available on the effects of cumulative impacts. The real question is whether the impact forces exceed the bonding strength of the pore ice which is, once again, dependent on water content and temperature. McKenna Neuman's 1989 study suggests that they do. It must not be forgotten that entrainment by impact is only possible when some initial particles are entrained by the wind without the benefits of particle impact.

3.3.4 Particle release by sublimation

Initiation of aeolian processes on frozen exposed surfaces occurs as interstitial ice sublimates and releases grains to entrainment. The sublimation-entrainment process is a complex one influenced by surface and microclimate characteristics such as grain size and shape, pore ice content, temperature, wind, and humidity. Little research is available on the interaction between these variables and the sublimation-entrainment process. Only three studies have investigated loose-particle production by sublimation from frozen surfaces as an aeolian process: an experiment on frozen soils by de Jong and Kachanoski (1988), a cold-laboratory experiment by McKenna Neuman (1990b) and a field experiment by van Dijk (1993; van Dijk and Law 1995). The sublimation process has enjoyed slightly more popularity as a microclimate/evaporation problem (Seligman 1963; Branton, Allen and Newman 1972), as a permafrost-material drying problem (Yershov, Gurov and Dostovalov 1973; Yershov *et al.* 1978; Wellen 1979; Johansen, Chalich and Wellen 1981; Gobelman 1985; Huang and Aughenbaugh 1987), and for other reasons (Thorpe and Mason 1965; Luikov and Lebedev 1973; Lin 1981, 1982; Aguirre-Puente and Sukhwal 1984). That many aspects of sublimation remain poorly understood will become evident in the following description of variables influencing sediment release.

3.3.4.1 Temperature

Ambient temperature is a prominent variable in the sublimation literature. Sublimation is limited to temperatures below 0°C by definition because the change from a solid to a vapour without melting cannot occur above the melting point of ice. The intensity of sublimation is greatest just below the freezing point (-1°C) and decreases rapidly as the temperature is lowered (Huang and Aughenbaugh 1987). In one study, the sublimation rate at -1°C was four times as great as that at -12°C (Huang and Aughenbaugh 1987) and in another study the rate at -5.6°C was twice that of -12.6°C (de Jong and Kachanoski 1988). Sublimation can occur at any temperature below 0°C, that is, there is no naturally-occurring lower limit, but the rate continues to decrease with lower temperatures as available heat energy decreases (Law and van Dijk 1994). Experimentally, pore-ice sublimation has been observed at temperatures as low as -25°C in the laboratory (McKenna Neuman 1990b) and at temperatures as low as -23°C under field conditions (van Dijk and Law 1995).

The variation of sublimation rate with temperature is conceptually represented in figure 3.6. Because of differences in test materials, duration, and measurement, it is not possible to assign values to the x- and y-axes. The shape of this relationship cannot be confirmed by most experiments which measured temperatures at two or three discrete intervals (Gobelman 1985; Huang and Aughenbaugh 1987; de Jong and Kachanoski 1988), although two such studies did state that the relationship is curvilinear (Aguirre-Puente and Sukhwal 1984; McKenna Neuman 1990b). The only data set with a range of temperatures produced a weak linear correlation (r^2 = 0.23 in van Dijk 1993); however, the study did note that this line is not valid at colder temperatures (because the x-intercept would denote a lower temperature limit of approximately -24°C) and a visual inspection of the data points suggests that a curve could also fit the data. Thus, the curve in figure 3.6 best represents the information that has been assembled at this time: sublimation decreases with temperature, the decrease is more rapid at higher temperatures and there is no lower temperature limit. Sediment release because of pore-ice sublimation can be represented by a similar curve.

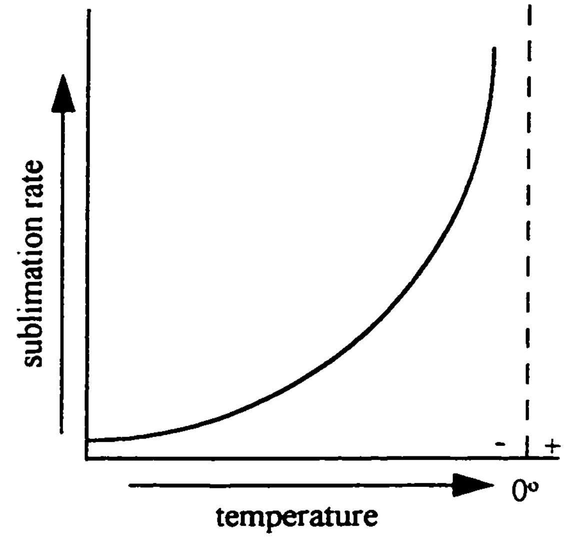


Figure 3.6 Variation in sublimation rate with temperature

Unfortunately, no clear distinction between air and surface temperature has been made in the research. Frozen soil temperature influences the temperature gradient between the surface and the air (Law and van Dijk 1994). Only the Russian studies (Yershov, Gurov and Dostovalov 1973; Yershov *et al.* 1978), Wellen (1979) and van Dijk (1993) measured the internal or near surface temperature of the frozen material. In the Russian studies and Wellen (1979), the results of the frozen sediment temperatures were not discussed, and in van Dijk (1993), the sediment temperatures corresponded closely to ambient temperature because the frozen test blocks were suspended in the air. The rapid adjustment of frozen test blocks to ambient temperature had occurred in McKenna Neuman's 1990b experiment and the measured air temperature was considered to be a good approximation of block temperature. The approximation of surface temperature by air temperature is less successful in a natural environment, especially during the winter months when soil temperatures just below the surface increase with depth and heat is transferred upward throughout the day and night (Rosenberg, Blad and Verma 1983). Because moisture also moves along temperature gradients (from warm to cold), the winter heat flow from the ground to the air (from a warm to colder temperature) can potentially be used to indicate the upward transfer of vapour which occurs in winter (Woo 1982).

3.3.4.2 Humidity

A fundamental aspect of sublimation is the transfer of mass in the form of water vapour from the ice surface to the boundary layer. The dynamic exchange of water molecules is always occurring to some degree, and the ice surface is bounded by freely mobile water molecules which exert a vapour pressure on the surface (Seligman 1963). The saturated vapour pressure of ice is the pressure exerted by the vapour when a state of equilibrium has been attained between the ice and its vapour (Jumikis 1966). When the air above ice is not saturated, an ice-to-air vapour gradient exists and molecules will diffuse into the air, thereby increasing the pressure exerted by the vapour (Oke 1987). As the vapour density of the boundary layer increases, the gradient is weakened and eventually (when the air is saturated with water vapour) an equilibrium is established "where the molecules escaping to the air are balanced by those returning to the [ice]" (Oke 1987, 64). Saturated vapour pressure is temperature-dependent (figure 3.7): as the

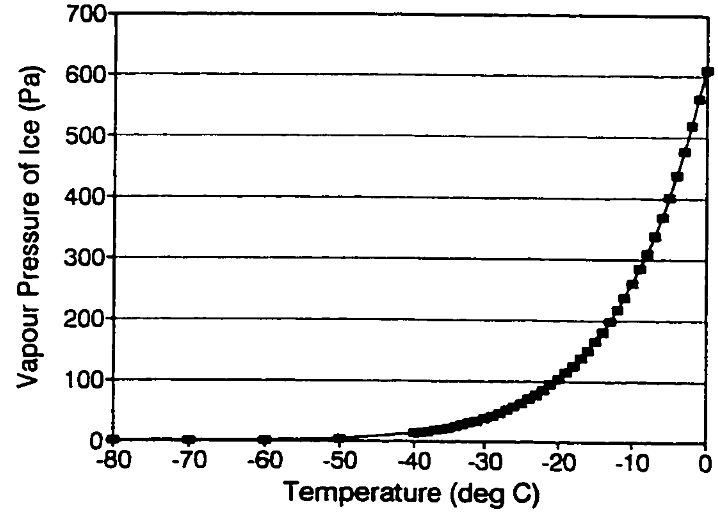


Figure 3.7 Variation in saturated vapour pressure over ice with temperature (data from *C.R.C. Handbook of Chemistry and Physics*, 1990-1991)

ice temperature is rises, the kinetic energy of the molecules increases, more molecules are able to escape, and the saturated vapour pressure increases (Oke 1987). Therefore, "as the temperature rises, ice will tend to give off more and more of its component molecules into vapour; as the temperature sinks, more and more of the molecules in the vapour will reattach themselves to the solid ice" (Seligman 1963, 27). In a frozen sediment surface, the pore ice is ordinary ice and the vapour pressure will be similar to the vapour pressure over pure ice of the same temperature (de Jong and Kachanoski 1988). Relative humidity relates partial pressure to the saturated vapour pressure at a given temperature and indicates how saturated with water the atmosphere is (Giancoli 1988). Sublimation is one process in which a total and temperature-independent moisture content of the atmosphere is less useful than an expression of the temperature-dependent degree of saturation. Only one of the studies made direct measurements of the vapour pressure over the surface (de Jong and Kachanoski 1988), while the majority measured relative humidity (Seligman 1963; Thorpe and Mason 1965; Yershov, Gurov and Dostovalov 1973; Yershov *et al.* 1978; Wellen 1979; Gobelman 1985; Huang and Aughenbaugh 1986; McKenna Neuman 1990b; van Dijk and Law 1995).

The empirical research substantiates the relationship between sublimation and atmospheric humidity. The variation of sublimation rate with relative humidity is depicted in figure 3.8. As the relative humidity of the air increases, pore ice sublimation decreases (Gobelman 1985; van Dijk and Law 1995). When the air is saturated with water vapour (relative humidity is 100%), net sublimation loss is not expected and this has been confirmed by experiments (Wellen 1979; Yershov, Gurov and Dostovalov 1973).

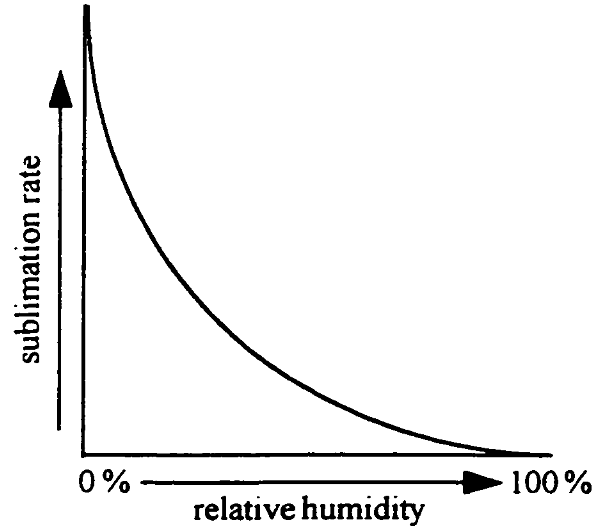


Figure 3.8 Variation in sublimation rate with relative humidity

When the relative humidity is above 80%, there is no significant change in the sublimation rate (Aguirre-Puente and Sukhwal 1984; McKenna Neuman 1990b), and at low relative humidity "the curve steepens up and the sublimation rate increases non-linearly with further decrease in the relative humidity" (Aguirre-Puente and Sukhwal 1984, 41). A curve similar to figure 3.8 would represent the relationship between relative humidity and loose particle production.

3.3.4.3 Wind Speed

Diffusion above the frozen soil is essential to maintaining the moisture disequilibrium and driving the sublimation process. If moisture is allowed to collect in the boundary layer immediately above the ice surface, this portion of the atmosphere may become saturated, thereby slowing down and/or halting the sublimation process. An increase in wind speed both reduces the thickness of the boundary layer and increases the gradient of vapour pressure across it (de Jong and Kachanoski 1988). The diffusion of sublimation-produced water vapour over the sublimation surface is enhanced by wind, especially if the wind is dryer than the immediate boundary layer atmosphere. In sublimation-entrainment, wind plays a double role as it transports loosened sand particles away from the surface along with the water vapour. Removal of loose grains from the frozen surface ensures that the active sublimation zone remains exposed to the atmosphere. This maintains sublimation as a surface process where the vapour does not have to diffuse through the pore spaces of a dried sand layer (Aguirre-Puente and Sukhwal 1984).

To date, the role of wind in the sublimation process has been seriously underestimated. Wind speed was not included as a variable in a number of the experiments, either because the studies were focused on environments with limited wind (the permafrost tunnel: Wellen 1979; Gobelman 1985; Huang and Aughenbaugh 1987) or because the studies were performed in a cold laboratory (McKenna Neuman 1990b). Recent field investigations (van Dijk and Law 1995) and cold wind tunnel studies (de Jong and Kachanoski 1988) confirmed earlier outdoor studies (Seligman 1963; Branton, Allen and Newman 1972) by indicating that wind speed is an important factor in the process.

Sublimation-induced deflation increases with increasing wind speed and, as illustrated in figure 3.9, the relationship appears to be linear (van Dijk and Law 1995). There is less information available to assess the effect of wind speed on pure sublimation, although Aguirre-Puente and Sukhwal (1984) state that the relationship is also linear.

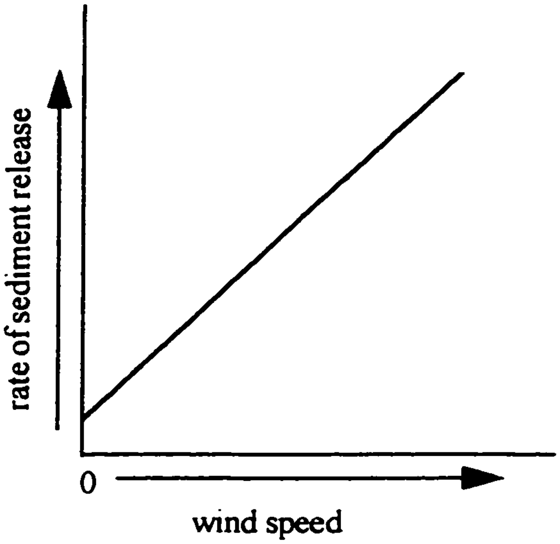


Figure 3.9 Variation in rate of particle release with wind speed

3.3.4.4 Water Content

There are two ways in which the role of water content can be evaluated: by looking at its effect on sublimation or by looking at its effect on particle release from the frozen soil. If the focus is loss of mass in the form of water vapour from the surface, then low water contents limit the total amount of sublimation possible. Higher water contents may enhance the initial sublimation rate by lengthening ice-air boundaries which serve as sublimation surfaces. When the focus is on particle release from the frozen ground, an increase in water content increases the amount of pore ice which must be sublimated before sand grains are released. Particle release decreases with increasing water content. These results were obtained in cold-laboratory and field experiments where surfaces with lower pore-ice contents deflated faster than those with higher water contents (McKenna Neuman 1990b; van Dijk and Law 1995). Van Dijk and Law (1995) suggest the relationship between particle release and sublimation is exponential (figure 3.10). All remaining studies measured only the sublimation loss of water vapour from the surface.

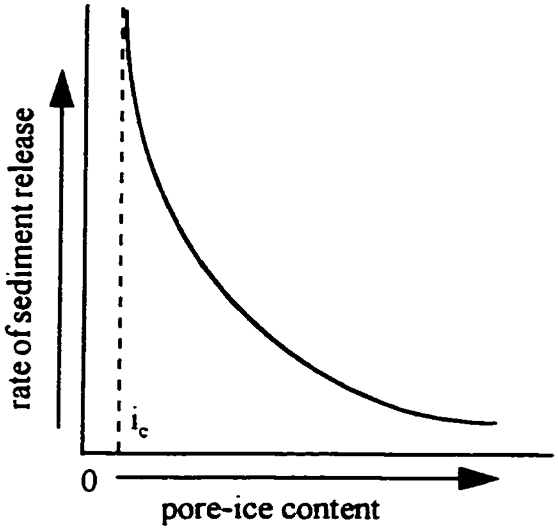


Figure 3.10 Variation in rate of particle release with water content; the lower limit i_c is the critical pore-ice content below which the surface is not cemented

The concept of a critical pore-ice content (i_c), adapted from aeolian discussions of a critical moisture content (Azizov 1977; Hotta 1988), is useful in the study of sublimation-entrainment. The critical pore ice content represents the lowest water content of the frozen soil at which the pore ice has a significant effect on aeolian entrainment. When the actual water content (w_i) of the frozen surface is less than i_c, there is insufficient pore-water to bind sand grains together when the surface freezes. When w_i increases above i_c the cohesion of the frozen surface also increases. If both i_c and w_i are known the following equation

$$w_i - i_c = w_{subl} \tag{3.13}$$

calculates w_{subl}, the amount of frozen water (%) which must be sublimated before entrainment can take place.

Real values for i_c are scarce. Van Dijk (1993) claims that frozen sand samples (d = 0.25 mm) fall apart at some water content below 5% and McKenna Neuman (1990b, 330) notes that at -13.5°C, frozen glass beads (d = 0.62 mm) were so weakly cohesive at 10% volumetric water content that they fell apart. With no reason for their assumption that liquid and frozen moisture would share the same critical value, de Jong and Kachanoski (1988) have adopted the 1500 kPa water content proposed by Chepil (1956) as the water content below which soils become wind-erodible. Given the different cohesive natures of liquid pore moisture and frozen pore ice, it is unlikely that a critical pore-ice content would equal the critical moisture content.

3.3.4.5 Sediment Properties

The effects of different sediments on sublimation-entrainment are poorly understood. The lone study on grain size and shape concludes that only grain shape has a statistically significant effect; particle release by sublimation increases as particle sphericity decreases (McKenna Neuman 1990b). An earlier study noted a general difference between silty material which retains its form as pore-ice sublimates and sand-sized material which quickly loses its cohesiveness and decreases its angle of repose (Wellen 1979). For frozen sands under no wind, grain release is not continuous but occurs in 1- to 2- mm thick sheets of particles which disintegrate under their own weight as cohesion is reduced to a critical level (McKenna Neuman 1990b). During entrainment by wind, grain size becomes important in determining the threshold shear velocity. The interplay between grain size, shape and sorting determine sediment porosity which affects frozen soil cohesion and vapour diffusion through any desiccated material (Aguirre-Puente and Sukhwal 1984).

3.3.4.6 Desiccated Layer

In the absence of entrainment, sublimation-drying produces desiccated material which slows down pore-ice sublimation in underlying soils. The sublimation rate decreases as the desiccated layer thickens (Yershov, Gurov and Dostovalov 1973). When dry sediment is not removed, the rate of sublimation approximates a power function with an initially-high rate, decreasing rate as the desiccated layer thickens, and a final low-but-constant rate of sublimation (Gobelman 1985; Huang and Aughenbaugh 1987). The rate deceleration stems from decreasing thermal diffusivity in the desiccated zone with a corresponding decrease in heat flux to the sublimation zone (Wellen 1979) and also from the influence of grains on the vapour diffusion processes (Aguirre-Puente and Sukhwal 1984). When a desiccated layer does not form on the surface (that is, when sediment is removed), the sublimation rate remains constant as long as microclimate conditions remain constant (Thorpe and Mason 1966; Wellen 1979).

3.3.4.7 Variable Interaction

Understanding deflation from frozen soils depends on understanding both the important variables and their interactions with each other. In previous paragraphs, general statements have been made about the effect of temperature, wind speed, relative humidity and total water content on the sublimation-entrainment process (table 3.3). Data are not yet available to quantify these relationships or even to assess the relative importance of variables. Some studies claim that temperature is the most influential variable (Gobelman 1985; Huang and Aughenbaugh 1987; McKenna Neuman 1990b), but these same studies did not consider wind speed. The studies which insist that wind speed is extremely important (Seligman 1963; Branton, Allen and Newman 1972; de Jong and Kachanoski 1988; van Dijk and Law 1995) measured different outcomes (sublimation from pure ice surfaces and frozen soil deflation). The dual role of wind as a transport agent for water molecules (sublimation) and soil particles (entrainment) makes it difficult to assess the importance of wind. Under different conditions, the relative importance of wind and other variables may change. An example of this is the demonstrated importance of temperature at low wind speeds.

Incompatible research methods may have fragmented the understanding of sediment deflation from frozen surfaces, but there are indications that an integrated model is not too far away. In recent analysis, a high correlation ($r^2 = 0.92$) was obtained when four variables (wind speed, temperature, relative humidity and total water content) were compared to sublimation-induced sediment loss from a frozen surface (van Dijk and Law 1995). The results confirm that optimal conditions for sublimation-entrainment are high wind speed and temperature, and low water content and relative humidity. The explanatory value of the equations is limited because test blocks were deflated from six sides instead of the single surface usually exposed in cold regions. More consequential are the implications--that it is possible to predict particle release from a frozen surface in terms of environmental conditions. Direct measurements are needed to produce similar predictions for natural surfaces in cold environments.

	Sublimation	Entrainment
Temperature	Sublimation can occur at any temperature below the melting point of ice. As the temperature decreases, sublimation decreases.	At lower temperatures, pore ice bonds are stronger and entrainment is restricted.
Humidity	As the relative humidity increases, sublimation decreases.	
Wind Speed	As the wind speed increases, sublimation increases.	If the shear velocity does not exceed the threshold for loose dry grains, no sand movement will take place. If the shear velocity exceeds the threshold for loose dry grains, loosened grains on the surface will be entrained. If the shear velocity exceeds a higher threshold for grains which have not been completely loosened from the surface, these surface grains will be entrained.
Water Content	If there is more ice available to be sublimated, more sublimation can take place.	As the pore ice content of the frozen surface increases, sublimation-induced entrainment decreases.
Desiccated Layer	If loosened grains are not removed from the surface, the sublimation rate slows down as the desiccated layer thickens.	When critical threshold velocities for loose dry surfaces are exceeded, the entrainment rate is limited by the availability of loosened grains.

Table 3.3 Variables affecting sublimation and entrainment in frozen-sediment deflation

3.3.5 Additional Cold-Season Variables

In cold environments, there are variables apart from ground freezing which influence the extent and timing of aeolian processes. Snow cover and surface ice protect underlying soils from deflation by wind and a fully-developed pebble lag can have the same effect. In contrast, deciduous vegetation dies back during the cold season and encourages surface deflation, while winds are often stronger in winter than in any other season. Little attention has been paid to these distinctly cold-season variables, but they have serious effects on the magnitude and frequency of cold-aeolian activity.

3.3.5.1 Snow Cover

The distribution and duration of snow cover are important to aeolian erosion and transportation. A continuous snow cover effectively halts aeolian processes (Koster 1988, 72; Dijkmans and Törnqvist 1990, 74), yet reports from many areas indicate that snow cover is rarely continuous. In the Antarctic, snow rapidly disappears by sublimation into the dry cold air (Calkin and Rutford 1974; Miotke 1984). In more temperate areas, strong winter winds redistribute the snow, exposing beach ridges and windward slopes of dunes and forming deep drifts in gullies, troughs and to the lee of dunes (Teeri and Barrett 1975; Carson and MacLean 1986; Riezebos *et al.* 1986; Law 1990; Belanger and Filion 1991; Lewkowicz and Young 1991; Ruz and Allard 1994). One effect of the redistribution is that snow fills in depressions and covers low vegetation in a process of early topographic saturation (Belanger and Filion 1991, 34). On the smoothed surfaces, wind-blown sand scatters widely and travels much further than it would over snow-free ground (Belanger and Filion 1991, 34). Niveo-aeolian deposits also suggest that snow also functions as an "extensive natural sediment trap" (McKenna Neuman 1993, 145).

The exposed surfaces left by the redistribution of snow become potential sources of aeolian sediments. The discontinuous snow cover exerts a strong influence over the spacing, timing and magnitude of sediment movement. Progressive exposure of source areas permits increasingly greater amounts of sediment movement and accumulation elsewhere (Lewkowicz and Young 1991, 206). Large interannual fluctuations in snow cover--which are typical (Dijkmans and Törnqvist 1990, 78)--produce corresponding fluctuations in sediment movement which can be recorded in niveo-aeolian deposits as varying thicknesses of snow, sand, and mixed snow and sand. Despite the variability of discontinuous snow cover, a number of authors refer to characteristic sections of their study areas that are snow-free for most of the winter (Teeri and Barrett 1975; Carson and MacLean 1986; Riezebos *et al.* 1986; Law 1990; Ruz and Allard 1994).

3.3.5.2 Surface Ice

Like snow, surface ice protects underlying soil from the erosive effects of the wind. Unlike snow, surface ice cannot be redistributed by wind because cohesion between ice crystals is too great. Surface ice is often discontinuous in nature and forms in depressions where the water table is high or runoff from surface melting collects when it cannot seep through the underlying frozen ground. Ice also forms as dense snow hardens and even infrequently when wave run-up and washover freezes on the beach. Through sublimation, wind is able to reduce ice thickness and extent, thereby gradually exposing more sediments.

3.3.5.3 Pebble-Lag Surfaces

The formation of protective pebble-lag surfaces has been noticed in many cold environments (Calkin and Rutford 1974; Miotke 1984; Riezebos *et al.* 1986; Swett and Mann 1986; Marsh and Marsh 1987; Law 1990). The lag surfaces (also called pavements) are formed as the wind removes the erodible grains from the surface and leaves behind pebbles which are too large to be moved by wind. These pebbles shelter the remaining erodible grains from the effects of the wind.

3.3.5.4 Vegetation

With respect to cold aeolian processes, vegetation is most notable for what it does not do. In warm seasons and areas, vegetation can be extremely effective in slowing down the wind near the surface and protecting soils from erosion. Changes to vegetation before the cold season enhance the seasonality of winter processes. Law (1990) observed that deciduous and herbaceous vegetation lose their leaves or die down completely in the fall, leaving a bare sand surface which has no protection from strong winter winds. The change from summer to fall can be from as much as 70% cover to nearly unvegetated. Larger deciduous vegetation which lose their foliage but do not die down increase their porosity, thereby decreasing the drag they exert on the wind. These trees can maintain a portion of their protection during the winter although they lose approximately 40% of their sheltering effect when they become leafless (Nord 1991).

3.3.5.5 Seasonal Winds

The significance of cold-aeolian activity in an area's annual sediment budget can be enhanced when winds are stronger in winter than in other seasons. This is true in temperate latitudes of the northern hemisphere where arctic and polar air masses reach further south in the winter than the summer (Briggs *et al.* 1993). These cold, dry air masses lead to the formation of sequential cyclones which carry stormy weather and strong winds with them. In studies of cold-aeolian phenomena, high energy winds in the winter have been noticed on Great Lake shorelines (Dozier, Mitchell and Marsh 1976; Marsh and Marsh 1987; Law 1990), the coast of Hudson Bay (Ruz and Allard 1994), in Western Greenland (Dijkmans and Törnqvist 1990), and northwest Scotland (Ballantyne and Whittington 1987).

3.3.6 Cold Environments and Aeolian Entrainment

Cold-aeolian activity is a complex assembly of interacting variables. The restrictions, supply mechanisms and environmental variables are summarized schematically in figure 3.11. Spatially, sediment supply is restricted by snow cover, surface ice and pebble-lag development. Snow cover and, to a lesser degree, surface ice are dynamic restrictions. Their spatial influence increases with new inputs of precipitation and decreases with moisture-transfer processes governed by wind speed, temperature, humidity, and available energy. On exposed areas of frozen sand, erodibility is affected by sediment characteristics, vegetation and water content. There are three possible methods of sediment entrainment. Fluid entrainment may occur under very strong winds from frozen

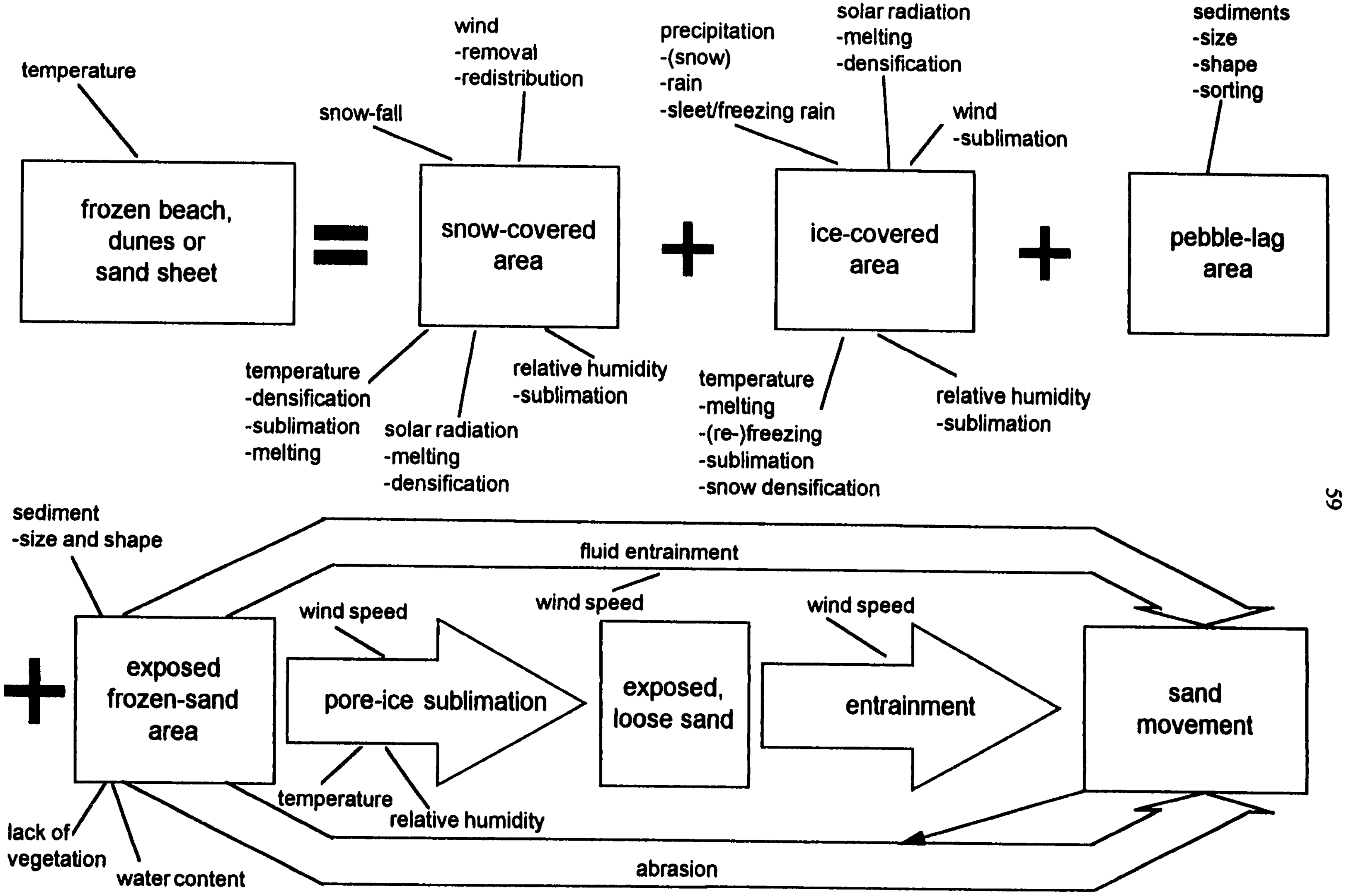


Figure 3.11 The cold-aeolian equation

sediments with low amounts of pore ice. With larger water contents and weaker winds, pore-ice sublimation is necessary to release sand grains for entrainment. Once movement has been initiated, saltating particles can entrain downwind particles through impact.

In cold-aeolian environments, limits to sediment supply and means of overcoming or reducing constraints result from interactions between microclimate (wind, temperature and relative humidity) and surface (sediments and moisture as pore ice, surface ice and snow). It should, therefore, be possible to describe and predict sediment supply using information on microclimate and surface conditions. As a specific example, consider a water content of 0%: both relative humidity and temperature have little effect, transport can be predicted from wind speed and sediment size using accepted equations, and aeolian activity essentially takes place over the 'ideal' surface. This ideal case has a large body of research attached to it, whereas supply-limited transport is poorly understood. Similar statements to the one above are not yet possible for specific water contents above 0%, let alone for the range of temperatures, humidity and wind speeds that occur in cold environments. The current status of knowledge is limited to an acknowledgement of important variables, a qualitative understanding of cause and effects, and a precursory set of equations to predict sublimation-entrainment.

3.4 Summary

Aeolian entrainment occurs when the forces exerted by wind on a grain in the sediment bed are greater than the forces holding the grain at rest. On an ideal surface, fluid wind and drag forces act against inertial forces in the form of weight and interparticle cohesion. For grains greater than 0.1 mm diameter, threshold friction velocities are largely a function of grain size. Complex surfaces influence entrainment by modifying the wind flow over the sediments or increasing the resistance of surface grains to movement. On wet surfaces, for example, pore water increases surface cohesion, and threshold friction velocities increase as the surface moisture content increases. In cold environments, the pore water freezes, increasing the surface cohesion many times as the sediment particles are cemented together by pore-ice. Fluid entrainment of surface grains is unlikely from frozen wet surfaces. Sediments are released from the cemented surface as sublimation removes the interstitial ice. Particle release by sublimation depends on local temperature, relative humidity, and wind speed as well as surface water content, sediment properties and thickness of a desiccated layer at the surface.

Interactions between local conditions, frozen sediments, particle release by sublimation and aeolian entrainment remain poorly understood. Quantitative information about the constraints posed by frozen sediments on aeolian processes is simply not available. In particular, boundary conditions and relationships between water content, temperature, cementation, and aeolian activity remain undefined. Limited information is available on the relationships between sublimation-induced particle release from frozen surfaces and various microclimate and surface variables. Further research is needed before sediment supply rates can be predicted quantitatively.

The supply limitations posed by frozen sediments and the mechanisms which enable sediments to move by wind fit into the complex system that is the cold-aeolian environment. Complications include snow, surface ice, pebble-lag development, vegetation and seasonal winds. The role of aeolian activity in this environment is determined by the interaction between exposed frozen sediments, pore-ice sublimation, and entrainment. Quantitative field measurements are as important to understanding cold-aeolian activity as data on processes. A combination of both are required to produce a coherent framework for understanding cold-aeolian activity.

Chapter 4

RESEARCH METHODS

> *Even if you're on the right track, you'll get run over if you just sit there.*
> Will Rogers

A variety of methods were employed to investigate cold-aeolian activity. Controlled-temperature experiments examined the supply-limitations of frozen exposed sand. Semi-controlled field experiments defined the relationship between local conditions and sediment release from the frozen surface. Both sets of experiments defined variables and relationships which are essential to cold-aeolian activity. These data were integrated with the background information from chapter three to develop a predictive model. The process of model-building links the various study methods, from collecting original data to forming the algorithm, and from transforming data into model format to testing and using the completed model. Field measurements of sediment erosion, transport and deposition provided reference points against which model accuracy was evaluated. Measurements of beach characteristics throughout the year and at various locations within the study area furnish spatial and temporal contexts for the study and model use. Microclimate data collection was crucial to several stages of the research including field experiments, field measurements and establishing the study context.

4.1 Controlled-Temperature Experiments

Experiments at controlled sub-zero temperatures produce valuable data on how water content and temperature affect aeolian activity through frozen-sand cohesion. In the experiments, frozen sand samples with specific water contents were exposed to various sub-zero temperatures to produce different amounts of pore-ice cohesion. Observations and cementation testing established boundaries for a number of categories describing the cohesion. Each category was assessed with respect to the sediment's potential to move by wind action. Unconfined compression tests delineated the moisture-temperature-cohesion relationship in more detail for samples which exhibited cohesion when unconfined.

Analysis of test results produces a moisture-based classification for frozen sands with an explicit focus on potentials for aeolian erosion.

4.1.1 Experiment Background

There is no standard test method for frozen sand cohesion. The literature suggests that engineers are more interested in the ability of frozen soils to bear loads than to have grains plucked from them, and most soil scientists study non-frozen soils. As a result, classifications of frozen soils with respect to cohesion remain very broad and are based on visual assessments (Swinzow 1970, 2; Tsytovich 1975, 21; American Society for Testing and Materials D4083-89 1994, 488).

Direct measurements of cohesion are difficult, but pore-ice bonding does produce visible changes in the soil's characteristics. Internal cohesion from moisture in non-frozen sands permits steeper angles of repose than the lack of cohesion in dry sands. The rigid crystal lattice in frozen sands produces more dramatic changes to the angle of repose. In fact, cohesive frozen soils can exceed 90 degree slopes and maintain angles through the entire 360° range. As pore-ice cohesion increases, the frozen soil's resistance to chipping, breaking and crushing also increases. Furthermore, short-term soil strength is directly related to the cohesion produced by pore ice.

The behaviour of frozen soils, from angle of repose through resistance to crushing, is observable and measurable, and therefore can be used to produce a quantitative classification of frozen-soil cohesion. The broadest classes result from simple observations of frozen samples which are unconfined, that is, removed from any surrounding soil or supporting container walls. The shape to which the frozen sand tends is a good initial indicator of cohesion. More detail about cohesion on an ordinal scale results from simple tests to determine sample resistance to being crushed. Quantitative measurements of frozen soil strength produce a ratio-scale classification. The strength measurements are limited to samples which are cohesive in an unconfined state.

The cohesion of frozen sand was quantified by three tests using controlled temperatures and water contents. Visual observations and cementation testing combined to produce an ordinal classification for frozen sands over an entire range of water contents. Unconfined compression tests produced detailed data on a subset of possible water contents. The description of methods follows the chronological order of testing: visual observations, unconfined compression tests, and cementation tests. Unfortunately the author did not encounter the cementation-testing method until after the other tests had been completed.

In September and October 1995, compression tests and visual observations took place in a controlled-temperature chamber at the University of Waterloo. The walk-in freezer, maintained by the Department of Earth Sciences in ESC123, had roughly 4 square metres of floor space available for sample storage and testing. Testing equipment stayed in the chamber throughout the entire two-month period; this arrangement prevented severe temperature fluctuations from affecting machinery parts and tainting test results. When the chamber temperature was changed, equipment and samples were given at least 12 hours to acclimatise before testing resumed. An HMP35CF probe monitored temperature and relative humidity; a Campbell Scientific 21XL datalogger sampled values every 5 seconds and recorded half-hour averages.

4.1.2 Visual Observations

Visual observations established a broad classification for frozen-sand cohesion. Specified amounts of distilled water and dried sand were mixed thoroughly, packed into square molds, and frozen at the test temperature for no less than 12 hours. During the test, each frozen sample was removed from its mold, observed, and categorized according to table 4.1 (data-sheet O-1 in appendix B). Frozen samples corresponding to a complete range of water contents (0% to 23%) were tested at each temperature. The results delineated water content and temperature boundaries for the categories in table 4.1. Unconfined compression testing could only be performed on samples which exhibited complete cohesion (category C).

Category	Observation of frozen sample when it is removed from mold
A: no cohesion	sample falls apart completely; there is no aggregation of grains
B: partial cohesion	sample falls apart, but clumps of sand are apparent
C: complete cohesion	sample is a coherent mass which retains the shape of the mold
D: oversaturation	sample is a coherent mass, but ice is not restricted to the pore spaces

Table 4.1 Categories for observations of prepared frozen sand samples

4.1.3 Unconfined Compression Tests

The unconfined compression tests followed method D2166-91 outlined by the American Society for Testing and Materials (1994). Specific amounts of distilled water and dried sand were mixed thoroughly, packed into cylindrical molds, and frozen at the test temperature for no less than 12 hours. The cylindrical samples had nominal dimensions of 10 cm in height and 4.2 cm in diameter for a height/diameter ratio of 2.4. A screw-driven universal testing machine set at a head speed of 0.5 mm/min performed the uniaxial unconfined compression tests (figure 4.1). The axial force and deformation produced in the compression of each specimen were displayed on analog dials and recorded at 15 second intervals during each test. Failure was defined as the instant the compressive stress dropped and was often accompanied by a noticeable fracture in the sample. After testing, each specimen was sketched, the diameter of the maximum bulge was recorded, and the water content of the sample was determined by oven-drying (data-sheets UCT-1 and S-1 in appendix B). When a statistically significant number of tests had been run at a specific temperature, the temperature was changed and the tests repeated.

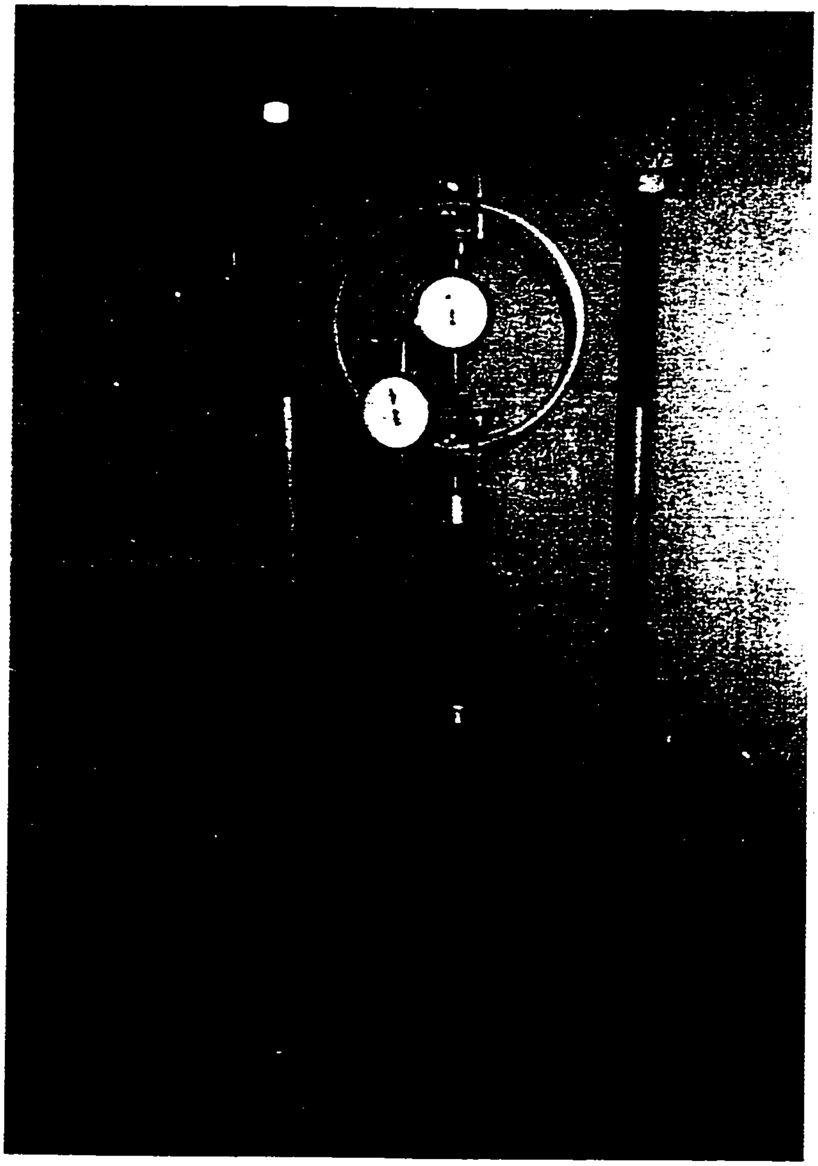


Figure 4.1 Frozen sand sample undergoing unconfined compression testing

Test results were analysed statistically to gain information about sample cohesion, water content and temperature. Regression analysis, with compressive strength as the dependent variable, examined water content and temperature as independent variables in turn. Assuming that cohesion is directly proportional to compressive strength, the analysis shows how temperature and water content influence pore-ice cohesion.

4.1.4 Cementation Tests

In March and April 1997, tests to further define frozen sand cementation were carried out at the Presqu'ile Research Station. The test procedure (table 4.2) was adopted from Hodgson's 1974 method for assessing the cementation of non-frozen soil. Specified amounts of distilled water and dried sand were mixed thoroughly, packed into cubic molds and frozen for no less than 8 hours at $-17^{\circ}C$ ($\pm 1.5^{\circ}C$). Samples tested under sub-zero temperatures outdoors were given at least 1 hour to acclimatise to the new temperature before testing. During the test, each 30-mm cube of frozen sand was removed from its mold, assessed according to the categories outlined in table 4.2, and the exact water content determined by the oven-dry method (data-sheets C-1 and S-1 in appendix B). At low water contents, a Soiltest CL-700 pocket penetrometer, operated according to manufacturers instructions (Soiltest Inc. 1964), provided values for unconfined compressive strengths up to 4.5 kg cm^{-2}. Up to 20 samples with water

Category	Description
uncemented	loose sand with no visible cohesion
very weakly cemented	sample is a cohesive mass which can be crushed between extended forefinger and thumb (force < 80N)
weakly cemented	sample cannot be crushed between extended forefinger and thumb but it fails when pressed underfoot on a hard surface by a person of average weight
strongly cemented	sample withstands weight of an average person but breaks or crushes when struck by a blow of energy 3 J (e.g., when object of weight x is dropped onto the sample through a distance of $0.3/x$ m)
very strongly cemented	sample is unbroken under a blow of 3 J

Table 4.2 Cementation categories and descriptions for 30-mm cubic samples of frozen sand (modified from Hodgson 1974)

contents ranging from 0 to 19% took part in each test, and sampling intervals were varied to reflect changes in cementation (for example, more blocks with low water contents were constructed and tested). The results delineate water content and temperature boundaries for cementation categories.

4.1.5 Putting Test Results Together

Controlled-temperature test results were combined into a classification of frozen sands. The classification matched specific water contents and temperatures to the various categories and descriptions of frozen-sand cohesion. Each category was assessed with respect to the aeolian activity possible on the frozen surface. The final moisture-based classification includes an explicit focus on potentials for aeolian erosion.

4.2 Field Experiments

Winter field experiments produce an equation for aeolian removal of sand from frozen-ground surfaces. In the experiments, frozen test blocks were lowered into preset beach cavities so that only the top sides of the blocks--level with the beach surface--were exposed. Following the example of an earlier study (van Dijk 1993), each test period occurred at night to eliminate pore-ice melting by direct solar radiation. The 12-hour weight losses were analysed with respect to temperatures, wind speeds and relative humidity measured at and near the experiment site. The analysis produced a predictive equation for frozen sand erosion based on wind speed, temperature and relative humidity. Details of the experiment equipment, procedure, and analysis are discussed below. Please refer to figure 4.2 for beach sites mentioned in the following discussion.

Thirty tests of experimental design in January-March 1995 produced an experiment method that was both accurate and efficient. The experiment structure was simple: test blocks of frozen sand were weighed, exposed to natural beach conditions for 12 hours (figure 4.3), weighed again, and weight changes examined with respect to beach processes (data-sheets G-1 and G-2 in appendix B). Specially-designed trays (figure 4.4) were

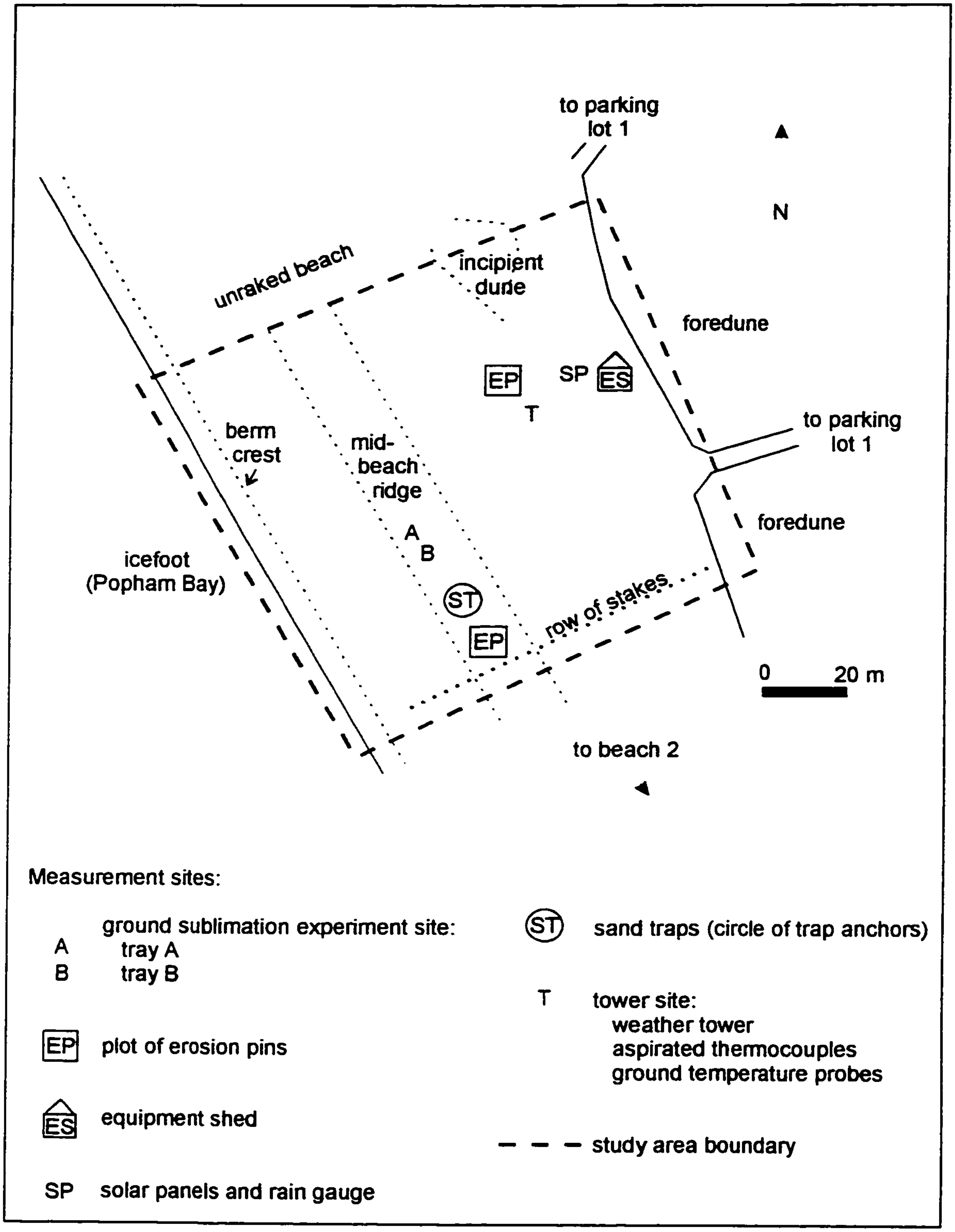


Figure 4.2 Presqu'ile Beach study area: measurement sites and significant features

Figure 4.3 Test blocks exposed to beach conditions

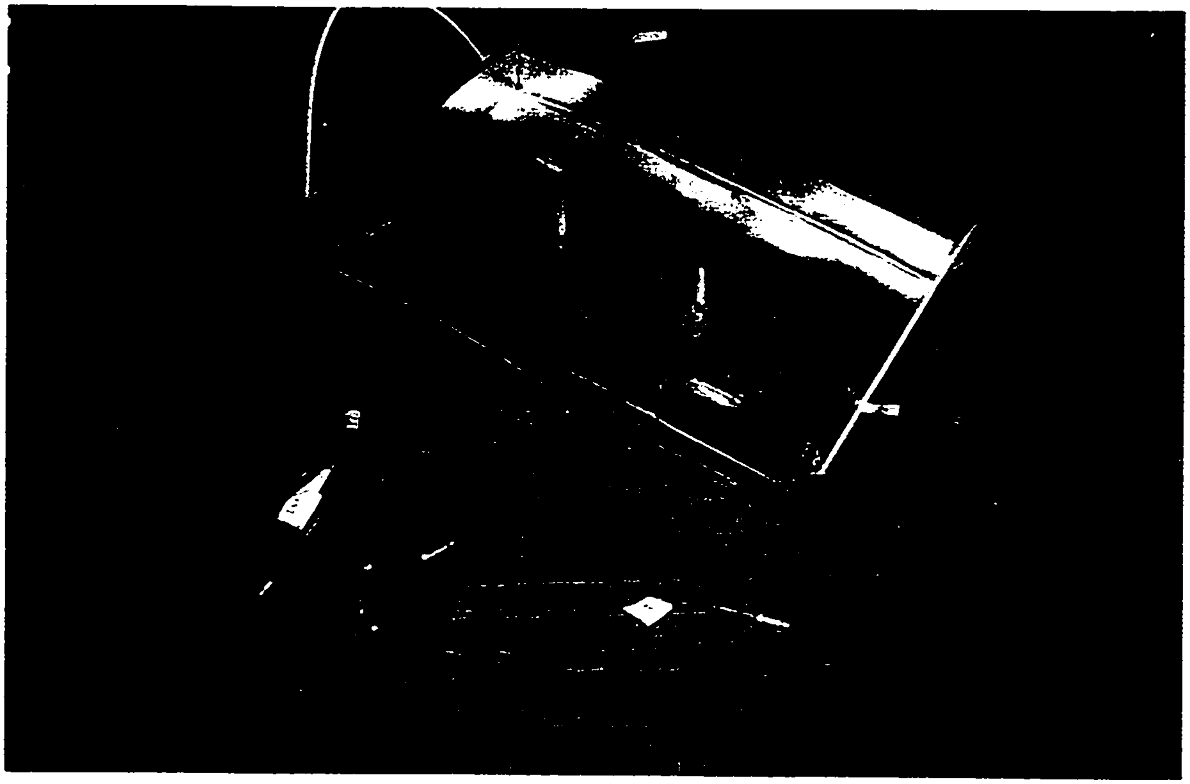


Figure 4.4 Aluminum tray with thermistors

used for frozen block transportation and beach placement. The trays were constructed of aluminum (less than 0.2 mm thick) whose high conductivity would allow block temperatures to quickly approximate surrounding temperatures in the frozen beach. Four thermistors were attached to each block tray, two flush with the bottom of the tray and two placed where they would measure block temperature a centimetre below the top surface. Attaching thermistors to the trays instead of inserting them in the test blocks produced the least interference between the test blocks, air, and frozen ground beside and beneath the blocks. Six blocks were placed in each tray; each block had nominal dimensions of 9.5 cm x 9.5 cm by 4.5 cm height and a starting weight of 0.55-0.65 kg. The test blocks were identified by their position on the trays (figure 4.5a) and specific water contents were used (figure 4.5b).

The beach location for the rectangular cavities into which the block trays were placed was established in January 1996. The initial experiment location was approximately 10 metres south-southeast of the weather tower and 15 metres west-southwest of the foredunes. Six of the 14 experiments at this location were unusable because drifting or falling snow covered the test surfaces. Attempts to clear the snow from a beach area around each

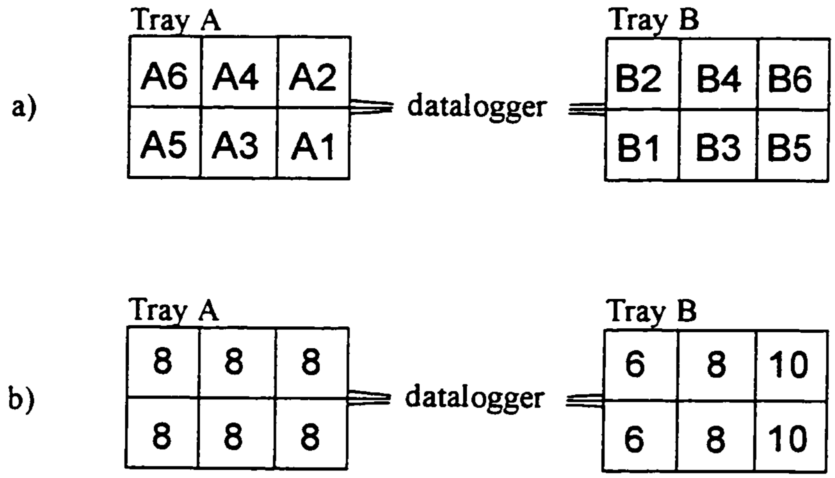


Figure 4.5 Test block locations on trays denoted by a) position and b) water content (% dry weight)

block tray were unsuccessful: not only did the creation of an unintentional moisture gradient encourage frost formation on the block surfaces, but the cleared area functioned as a sink for drifting snow. New rectangular cavities were constructed 30 metres to the west-southwest on a midbeach ridge which showed a tendency to being snow-free. When there was snow, the ridge was quickly cleared by the wind, and drifting snow from upwind locations would travel past this area to be deposited closer to the foredunes. The primary drawback of the midbeach location was its distance from the weather tower. Therefore, wind speed was measured at the site with an anemometer at a height of 1 metre, and air temperatures were measured with unshielded thermocouples at 5 heights (figure 4.6). Wooden beach covers prevented sand and snow from filling up the holes when they were not being used for experiments.

The concurrent measurement of beach and microclimate conditions with the field experiments permitted a detailed analysis of the variables which determine frozen surface erosion. Ground temperature below the test blocks, air temperatures at 5 heights and wind speed at a 1-metre height were measured at the experiment site. A microclimate station located within 50 m of the experiment site recorded wind direction, wind speeds at 5 heights, air temperature and relative humidity at 3.5 m height, net radiation, air temperatures at 5 heights (with shielded and aspirated probes), and ground temperatures at 6 depths. (Microclimate measurements are described in section 4.3.) For each variable, values for every 12-hour experiment were derived (averages or totals) and linear regression analysis was performed with the overnight weight loss as the dependent variable. Multiple regression analysis of the best independent variables yielded a predictive equation for frozen surface erosion.

Supplementary experiments investigated a wider range of water contents because the ground sublimation experiments were limited to three specific values. Eleven frozen blocks with water contents ranging from 3 to 22 per cent by mass were placed on the framework used by van Dijk in 1993. The experimental method was the same as van Dijk (1993) with the absence of temperature probes in the blocks. Weight losses over the

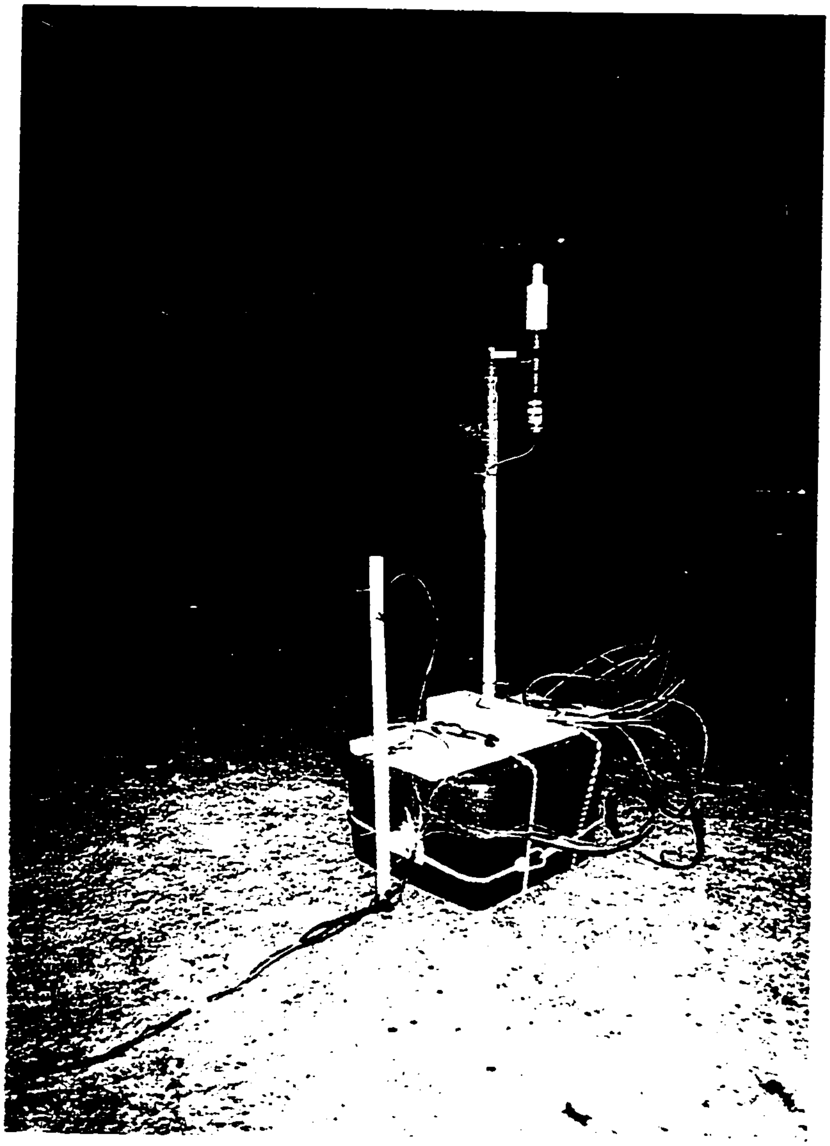


Figure 4.6 Mini-meteorological array at experiment site

12-hour periods were compared to the water contents of the blocks. The plotted curves illustrated a semi-logarithmic relationship which was defined by regression analysis. The moisture factor expands the predictions of the frozen surface erosion equation to a wider range of water contents.

4.3 Microclimate Data Collection

Presqu'ile Beach microclimate measurements are essential to winter research. In this study, microclimate data were used to analyse field experiment results, produce model predictions and develop the study context. Each winter an integrated array of sensors, datalogging equipment and support hardware yielded volumes of microclimate data to be analysed for general trends in winter processes. Portions of the data were extracted and further analysed for specific experiments and process measurements.

4.3.1 Yearly Installation

In late fall of each year, a complex array of microclimate equipment was installed at Presqu'ile Beach. The equipment monitored wind, temperature, humidity, and net radiation, but the yearly set-up changed from 1993-1997 (table 4.3) as new equipment became available, additional data were required and beach changes occurred. The most substantial changes occurred at the beginning of the 1995-1996 field season. In that year, the use of a compact shed to protect sensitive data-storage equipment accompanied a new tower design, increased power and data-storage capacity, the addition of aspirated thermocouples to the site, and more anemometers for wind-profile measurements. Equipment changes provided noticeably better data for the field experiments and only minor adjustments were needed before the 1996-1997 winter. Microclimate equipment is not left on the beach year-round because of the increased potential for vandalism when thousands of visitors use the beach during the summer.

4.3.2 Measurement Site

The measurement location was carefully chosen to provide the most accurate picture of beach microclimate. Important site requirements are adequate fetch for wind data and representative surfaces underneath air temperature and net radiation sensors (and above soil temperature probes). The site has to be free of vegetation, relatively ice-free during the winter (that is, not low-lying and prone to flooding), and needs sufficient fetches in dominant wind directions (figure 4.7). In 1995 the microclimate site was moved approximately 50 metres southeast of the original site when modified beach-raking

	'93-'94	'94-'95	'95-'96	'96-'97
measurement period	21 Nov - 12 May	1 Nov - 27 April	16 Dec - 20 March	29 Nov - 8 April
location	*site 1	*site 1	*site 2	*site 2
Air Temperature				
HMP35CF probe (shielded)	~5 m	~5 m	3.5 m	3.5 m
aspirated thermocouples (shielded)	—	—	0.03 m	0.06 m
			0.06 m	0.125 m
			0.12 m	0.25 m
			0.25 m	0.50 m
			0.50 m	1.0 m
Soil Temperature				
107 probes (thermistor	—	0.02 m	0.0 m	0.0 m
		0.04 m	0.0 m	0.03 m
		0.06 m	0.03 m	0.06 m
		0.10 m	0.09 m	0.12 m
		0.18 m	0.22 m	0.25 m
		0.34 m	0.47 m	0.50 m
Net Radiation				
Q*6 net radiometer	~5.5 m	~5.5 m	2.5 m	2.5 m
Humidity				
HMP35CF probe	~5 m	~5 m	3.5 m	3.5 m
Wind				
Young wind monitor (speed & direction)	~6.0 m	~6.0 m	6.5 m	6.5 m
3-cup anemometers (speed)	1.5 m	1.5 m	0.5 m	0.5 m
	3.0 m	3.0 m	1.0 m	1.0 m
	4.5 m	4.5 m	2.0 m	2.0 m
			4.0 m	4.0 m
			6.0 m	6.0 m
Precipitation				
tipping-bucket rain gauge	behind wind-surf hut	behind wind-surf hut	~2.5 m near equip't shed	~2.5 m near equip't shed

*Tower site 1 was approximately 60 metres NNW of tower site 2 indicated by "T" in figure 4.2; in 1995, park staff stopped raking the area around site 1

Table 4.3 Summary of microclimate equipment, heights, and measurement periods at Presqu'ile Beach from 1993-1997

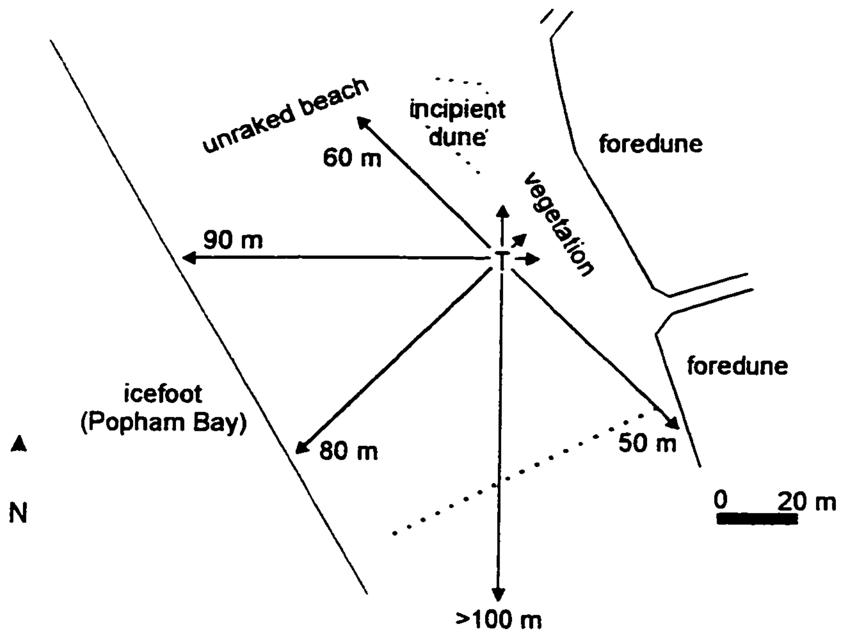


Figure 4.7 Fetch for Presqu'ile Beach weather tower in 1996-1997

practices reduced the fetch in the upwind direction. This new location was made possible by the removal of a building from the beach and continued to offer adequate fetch for measurements in 180° of direction.

4.3.3 Instrumentation

The microclimate equipment for Presqu'ile Beach are described below. Discussion centres on the instruments and hardware in operation in the final field season (1996-1997) and instrument heights are given in table 4.3 on page 74. The anemometers, wind monitor, shielded temperature and humidity probe, and net radiometer are pictured in figure 4.8 with the solar panels, equipment shed and rain gauge visible in the background.

Gill 3-cup anemometers measured wind speeds at five heights above the beach surface. The range of these instruments is 0 to 50 m/s with a threshold sensitivity of 0.5 m/s (Campbell Scientific Canada Corp. 1994). Each anemometer was installed on a horizontal bar extending from the weather tower to the northwest. Logarithmic heights

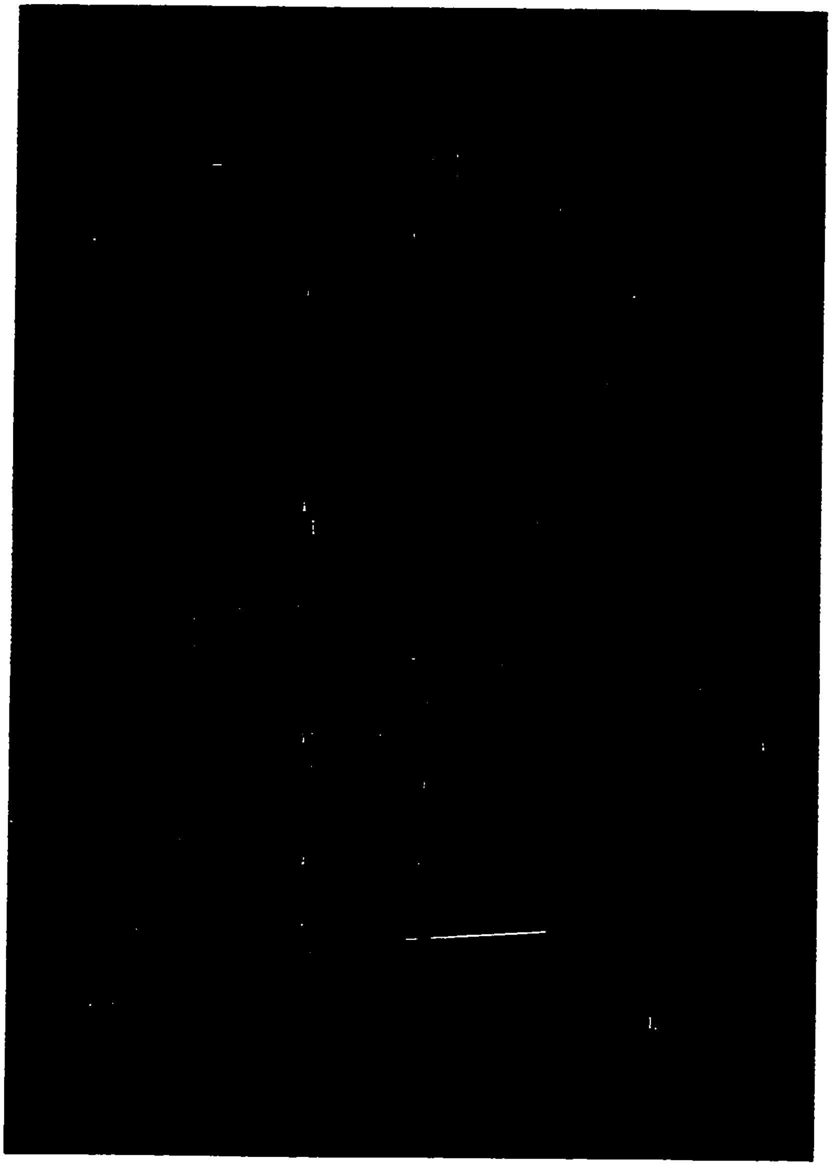


Figure 4.8 Presqu'ile Beach weather tower

were chosen for the vertical profile because the wind speed data would be used to derive the wind shear velocity, u*. The distance between the bottom anemometer and the beach surface was recorded regularly. A Young model-05103 wind monitor made an additional wind speed measurement at the top of the weather tower; the wind monitor has a range of 0 - 60 m/s, threshold of 1.0 m/s and accuracy of ±0.3 m/s (R.M. Young Company

1990). Wind speeds from the wind monitor were not included in wind profile data because the instrument was not vertically aligned with the three-cup anemometers.

A lightweight vane on the Young wind monitor indicated wind direction over the beach. The vane has a 360° mechanical azimuth with an accuracy of ±3 degrees, and threshold requirements range from 0.9 m/s at 10° displacement to 1.3 m/s at 5° displacement (R.M. Young Company 1990).

Air temperature measurements included a point measurement of temperature near the tower and a vertical profile of temperatures near the beach surface. A YSI 44002A thermistor in a temperature-humidity probe (Vaisala model HMP35CF) sampled the air temperature at the weather tower. The probe was protected from unwanted radiation effects by a model 41002 Gill multi-plate radiation shield. The thermistor's range is -53°C to +48°C and its accuracy is listed as typically better than ±0.2°C, although it could be ±0.4°C in the worst case (Campbell Scientific Canada Corp. undated). Air temperatures close to the beach surface were sampled by five copper-constantan thermocouples housed in aspirated shielding to prevent radiative heating of the sensors. The supplier specified the limits of error for the thermocouple wire at 1°C (OMEGA Engineering, Inc. 1995, H-3). The error caused by the aspirated housing has not been calculated but should be the same for each of the probes. A maximum error of 1°C is assumed for the thermocouple temperature measurements, and temperature differences can be assumed accurate to ±0.1°C.

Six thermistors measured soil temperature at different depths near the weather tower. Holes drilled into a wooden stake maintained set intervals between the Campbell 107 probes and ensured the vertical alignment of the sensors. The entire stake and probe assembly was placed in the ground before the onset of winter. Accurate depths for the probes beneath the surface were determined by regular measurements of stake height above the beach surface.

A HMP35CF probe was used to sense relative humidity at the site. The probe has a range of 0 to 100% relative humidity, and operates under temperatures from -20°C to +60°C with a temperature dependence of ±0.04% RH/°C (Campbell Scientific Canada Corp. undated). Measurement accuracy is ±2% RH from 0 to 90% and ±3% RH from 90 to 100% (determined at 20°C when tested against field references; Campbell Scientific Canada Corp. undated).

A Rimco tipping-bucket rain gauge recorded the rainfall at the microclimate site. The gauge was placed by the equipment shed on a raised platform; the height of the gauge ensured that the intensity of the rain going into the funnel was not been changed by nearby structures. The accuracy of the Rimco gauge was ±1% to 380 mm/hr (McVan Instruments, Ltd. 1991). Occasionally snow melting in the funnel would tip the bucket and produce an erroneous record. Visual observations of the times and types of precipitation over the winter allowed good and bad data to be separated. Snowfall throughout the winter was recorded as a combination of visual observations of snow cover on the beach and depth measurements with a metre-stick near the tower.

All of the microclimate instruments were connected by cable to the datalogging equipment located in the equipment shed. Two 21XL dataloggers, an AM416 multiplexer and two storage modules performed the data sampling and storage. The sampling interval was 15 seconds and the data were recorded as half-hour averages, maximums or totals. Data were transferred from the beach site to computer in storage modules.

A combination of solar panels and gel cell batteries supplied the power for the microclimate instruments and datalogging equipment. Two ten-watt photovoltaic cells were mounted on the platform with the rain gauge and faced south at a 52° angle to catch the maximum rays from the winter sun. The solar energy collected by each unit recharged batteries located in the equipment shed. A gel-cell battery supplied the power for the datalogger and multiplexer, and through them provided excitation voltages for the relative humidity and temperature probe (HMP35CF) and the wind monitor. Two marine batteries (connected in parallel) supplied the power for aspirating the thermocouple array.

4.3.4 Analysis

Organizing and analysing the vast amounts of data that were produced in the microclimate collection was a multistep task. The data were downloaded from storage modules to computer using the datalogger support software program SMCOM. With another datalogger support program called SPLIT, parameter files were written and executed to reduce the masses of data into specific reports (for example, daily summaries, wind speed profile data and so on). The reports were imported into a spreadsheet program where the data extraction and analysis took place.

4.4 Model-Building

Building a model produced a practical way for predicting and understanding cold-aeolian activity. The process of model-building follows a sequence of logical steps (figure 4.9). In the first stage, cold-aeolian phenomena are understood and defined. Then the cold-aeolian knowledge is transformed into a practical format using variables and relationships to structure the model. The transformation includes writing an operational computer program to generate a computer simulation model. Validity of the model is checked against real world data before the model can be utilized.

4.4.1 What is a Model?

A model is a simplified, often mathematical, description of a piece of the real world, used to assist calculations and predictions (Hawkins and Allen 1991, 931). Models take many forms depending on their purposes, subject matter, amount of detail, etc. The essential feature is that the model simplifies the problem, situation or system to the relationships between important variables (Penney 1985, viii). In so doing, models reduce ambiguity and describe complex situations with maximum parsimony (Jeffers 1982, 15).

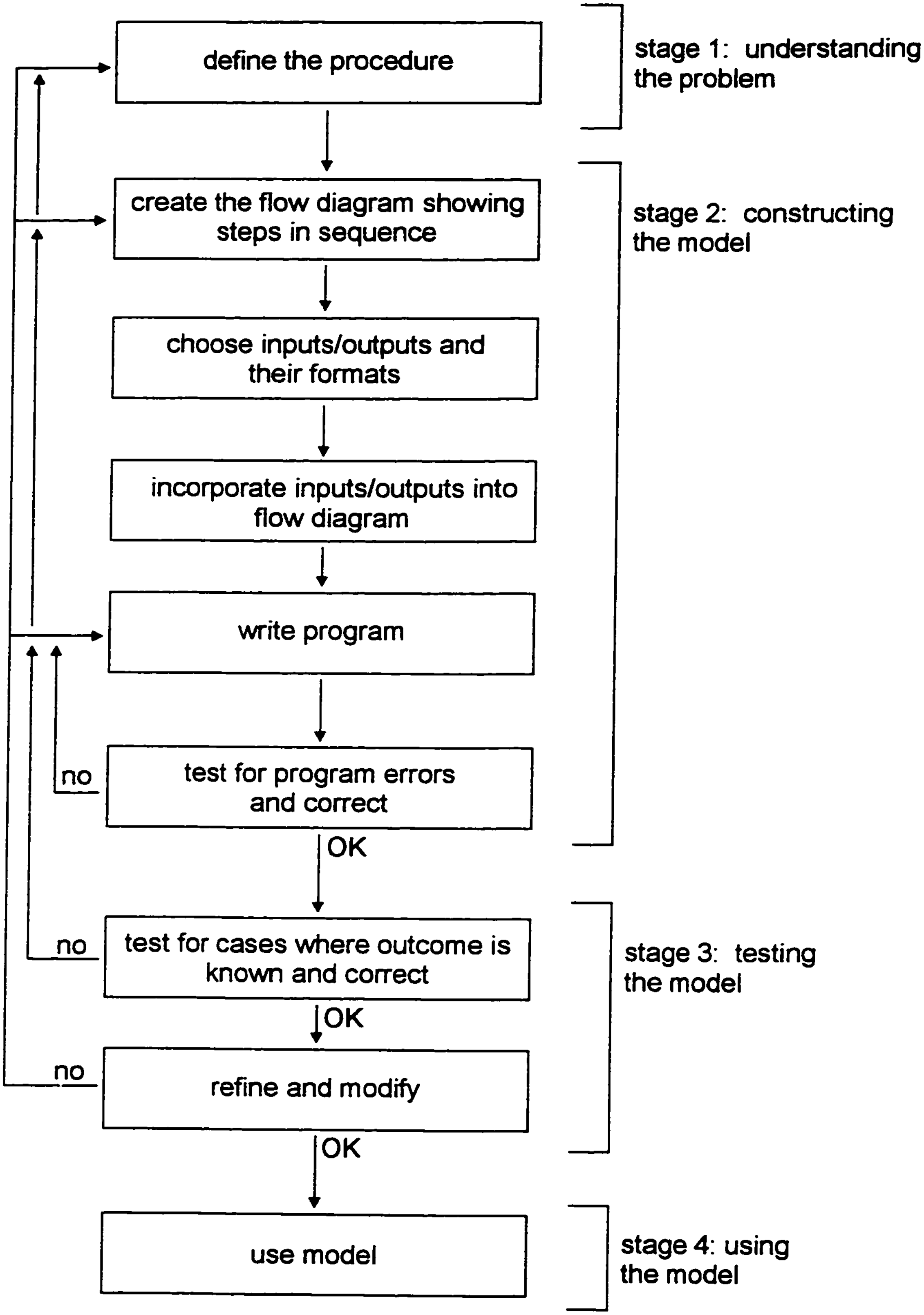


Figure 4.9 Building a model (modified from Kirkby *et al.* 1993, 9)

In physical geography, models simulate the effects of actual or hypothetical processes and forecast one or more possible outcomes (Kirkby *et al.* 1993, 3). *Deterministic* models produce a unique forecast for a given set of inputs, while *stochastic* models produce more than one forecast because of some random element in the process operation or inputs to the model (Kirkby *et al.* 1993). With respect to cold-aeolian activity, a simulation could use environmental conditions to forecast whether sand is moving or use more detailed equations to predict amounts of sand transported. Both types of simulations are deterministic because a unique result is assumed.

4.4.2 Understanding the Procedure

The most difficult stage of building a model is understanding the problem and defining it in a logical form. Study problems fall into two categories: *cognisant*, about which there is current knowledge, and *non-cognisant*, about which there is very little knowledge (Laing 1985, 38). For both of these, model construction demands that the significant variables be identified and important relationships be defined. This may require additional experimentation or new theoretical calculations. The correct balance between accuracy and simplicity requires clarity of thought. Conceptual diagrams, in which all variables are set down and relationships drawn between them, can be useful at this stage.

An assessment of available research, supplemented by experiments in some areas, was necessary for producing a logical understanding of cold-aeolian activity. The comprehensive review of literature (chapter 3) pointed to factors characteristic of cold environments and showed how they influence aeolian processes. The review indicated two main areas which needed clarification before a model could be constructed. Controlled-temperature experiments explored the variable of pore-ice cohesion and its relationship to aeolian processes. Field experiments confirmed major environmental variables and clarified relationships between these variables and outcomes of sand movement. The literature review and experiments produced a list of specific independent variables which exert the greatest influence over cold-aeolian processes. Relationships between the independent variables and aeolian processes of entrainment and sand transport were quantitatively defined.

4.4.3 Constructing the Model

During model construction, knowledge about the phenomena is converted into a chosen model format which can range from a concrete physical representation to an abstract mathematical expression. The format chosen for the model of cold-aeolian activity is a computer simulation. Advantages of this format are the computer's ability to handle large data sets and repeat calculations many times. The computer is ideally suited to processing the ranges of possible values for each independent variable and quickly calculating each unique forecast.

Producing a computer simulation requires logical thinking. The research problem must be understood and steps of the problem set out in a logical procedure with inputs and outputs carefully defined. Often this necessitates a flow chart to ensure proper sequencing and thoroughness. It is less difficult to write a program and put it into a chosen computer language when the phenomena's procedure is clear. A completed program must be tested and retested for program errors.

Constructing the computer simulation for cold-aeolian activity followed the steps outlined in the preceding paragraph. The flow diagram included independent variables, active processes and possible outcomes. Model inputs would be provided by the user and would consist of 12-hour values for independent variables. The computer model would perform the necessary calculations and then provide outputs concerning which processes were active, whether sand movement was taking place, and how much sand was released or transported. Q-Basic was chosen for the programming language because the author had some familiarity with it and it was used in Kirkby *et al.*'s (1993) discussion of computer simulation in physical geography. The program was tested for errors and corrected.

4.4.4 Testing the Model

Model testing is a repetitive process of checking model predictions against real world information and correcting for discrepancies between the two (figure 4.10). There are two separate phases to model testing. In the first, the model is compared to cases where the outcome is known. If the data used to test the model are independent of the data used to build the model, comparing numerical forecasts to real world measurements makes an exact test of model performance (Kirkby *et al.* 1993, 4). Discrepancies call for corrections to how the problem is understood, the flow diagram, and the computer program. In the second phase, the model is refined and modified as new data appear. In this way, conditions and outcomes outside the initial scope of the study are considered and incorporated into the model. Once again, corrections are made to how the problem is understood, the flow diagram, and the computer program.

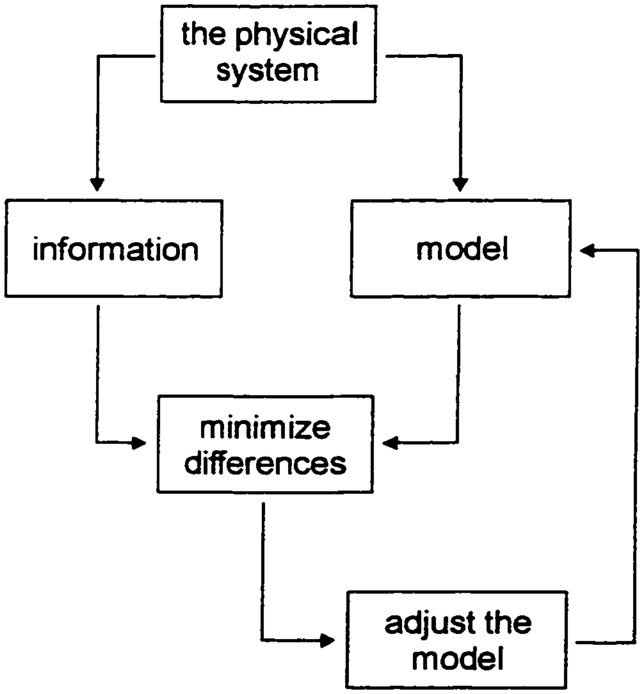


Figure 4.10 Comparing model predictions to real world information (after Kirkby *et al.* 1993, 132)

The model of cold-aeolian activity was tested against field measurements of aeolian activity and sand movement. Model forecasts, based on input conditions (from microclimate data and field measurements), were compared to real world outcomes (from field measurements). The significance of each discrepancy was assessed and corrections made where possible. The process of testing the model pointed to ways in which the understanding of cold-aeolian activity needs to be changed. Testing was restricted to the range of conditions used to set up the model, although new data were employed. The second phase of modifications--using new data to expand the outcomes of the model--was beyond the scope of this study and is left for future research.

4.4.5 Using the Model

Models can be used in a number of ways: as a didactic tool to illustrate how a system works, as a research procedure to investigate and/or experiment with a whole system, and as a forecasting instrument when actual predictions are required (Kirkby *et al.* 1993, 132-133). The cold-aeolian model has potential in each of the three areas. In this dissertation, the model's main use is to illustrate how cold-aeolian phenomena operate. The model combines variables and relationships into a unified framework. Thus, building and testing the model are especially important in showing how the understanding of the variables and processes compares to real world data on the same variables and processes. As a research procedure, the model can be taken through a number of possible combinations of variables and processes. Use of the model as a forecasting tool was beyond the scope of this study. Nevertheless, the model's ability to predict activity and sand transport will be valuable to managers and researchers alike.

4.5 Field Measurements

From December 1996 through March 1997, surface conditions and sand movement on Presqu'ile Beach were measured to provide real world data which could be compared to model predictions. Daily observations of the beach surface produced a record of thaws, snow and ice cover, and the duration and spatial extent of exposed sand. Sediment samples from exposed areas were tested for water content. The depths of beach erosion and deposition were recorded at erosion pins and wooden stakes, while winter sand traps collected sand moving across the beach. Analysis of surface, erosion, and sand transport data indicated timing and amounts of sand movement. These results were compared to model predictions in an assessment of model accuracy.

4.5.1 Beach Observations

Daily observations of the Presqu'ile Beach study area chronicled surface changes which limited or permitted sand movement. Each day the study area was inspected from the water's edge (icefoot) to the foot of the foredunes. The state of the icefoot was noted, and exposed sand, snow, ice, water, etc. on the beach surface were assessed using wooden stakes as benchmarks. Processes such as sand and snow movement were also logged. Based on the daily records, the portions of the beach from which sand was moving, or which had the potential for sand movement, were estimated. The comprehensive winter record produced estimates of when aeolian activity could take place.

4.5.2 Surface Water Content

The water content of the beach surface was determined by oven-drying soil samples taken from various locations on the beach. Sites were chosen in exposed areas where snow and ice were not protecting the beach surface. Whenever possible, samples were taken along the row of stakes and continued to the icefoot edge. Sampling frequency depended on the duration of snow- and ice- cover on the beach. Each sample was removed from the top 1-2 cm of beach sand and was identified by site; beach condition (thawed or frozen) was also noted. When the beach surface was unfrozen, a trowel was used to scrape surface sediments into a sample tin. When the beach surface was frozen, an impact-driven soil sampler (van Dijk and Law, in progress) detached frozen chunks of sand from the surface (figure 4.11). The water contents of all samples were found by oven-drying (American Society for Testing and Materials D2216-92 1994; data-sheet S-1 in appendix B) and applying the following equation:

$$\text{water content} = \frac{\text{wet mass} - \text{dry mass}}{\text{dry mass}} \times 100\% . \qquad (4.1)$$

Weighing precision was ±0.01g, and the final accuracy of water content measurements is estimated at ±0.1%. As one of the inputs in the cold-aeolian activity model, the measured water contents indicate potential aeolian erosion from the sampling sites.

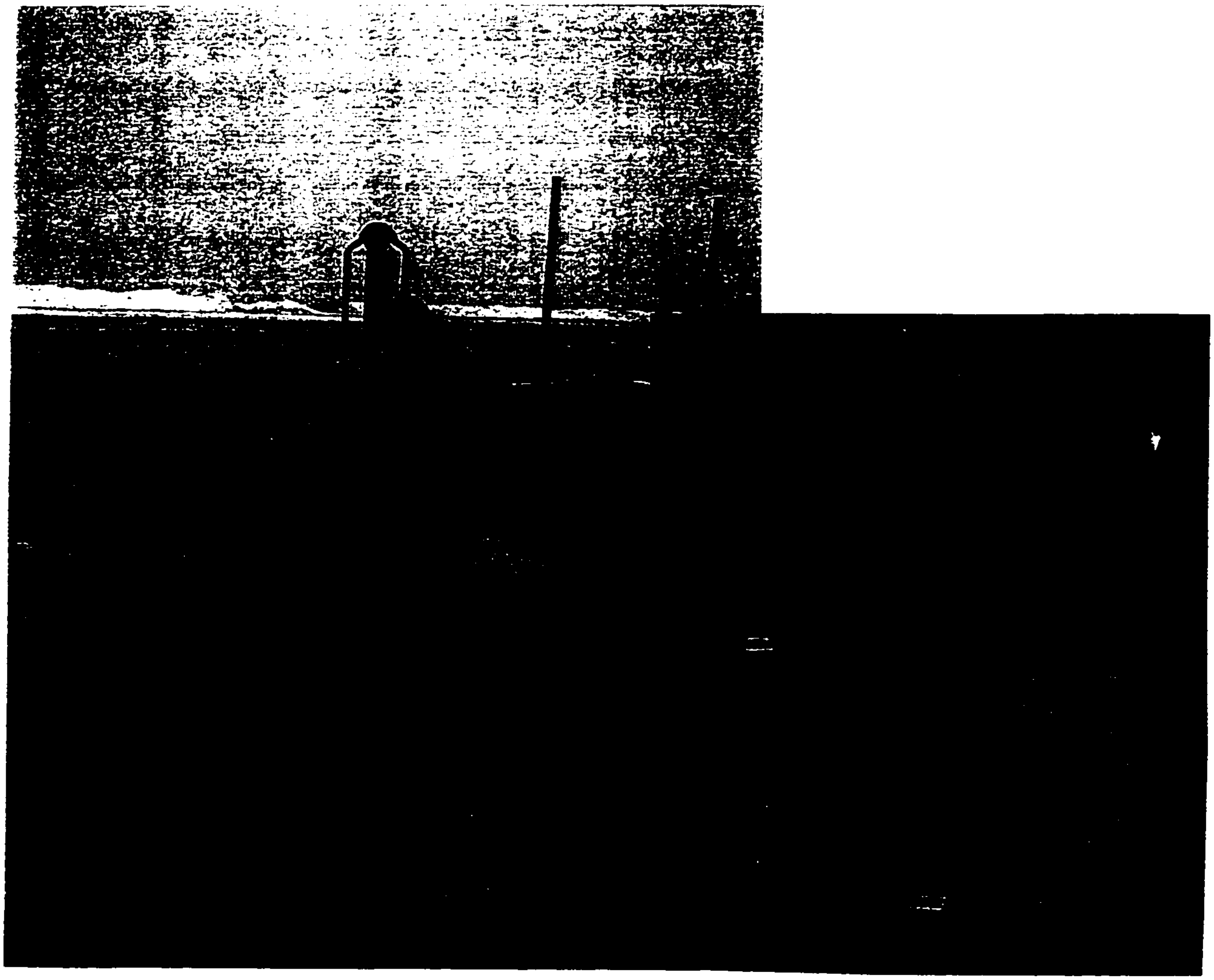


Figure 4.11 Impact-driven soil sampler in use at Presqu'ile: a) weighted slide-hammer is dropped to drive the coring-tube's cutting edge into the frozen ground and b) 'disks' of frozen sand detached by successive impacts were oven-dried to determine water content

4.5.3 Erosion Pins

Direct erosion of the beach surface was measured relative to metal erosion pins. The 45-centimetre long pins had diameters of roughly 2 millimetres and were inserted into the ground before freezing. For public safety and site protection, the pins were marked with coloured tape, placed in groups, and roped off from the surrounding area. Each plot had 9 pins in a square metre of beach: 3 rows of 3, with rows and columns spaced 0.5 metres from each other (figures 4.12 and 4.13). The bounded areas were 2 square metres and marked by four corner stakes (approximately 30 centimetres high) supporting clearly-

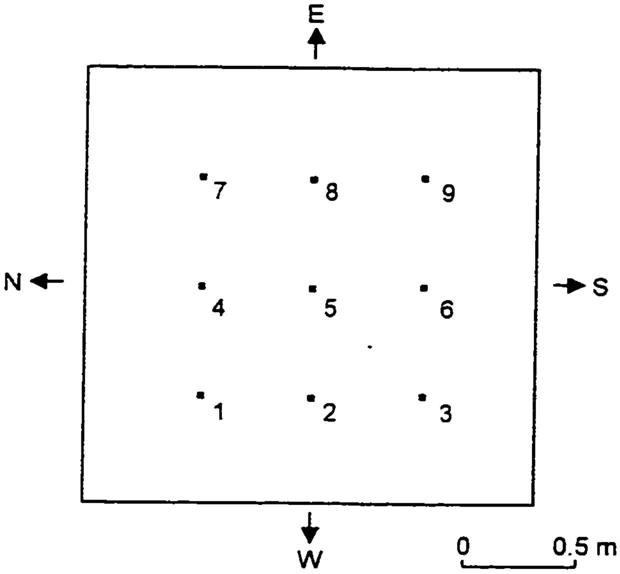


Figure 4.12 Plan view of erosion pin plot

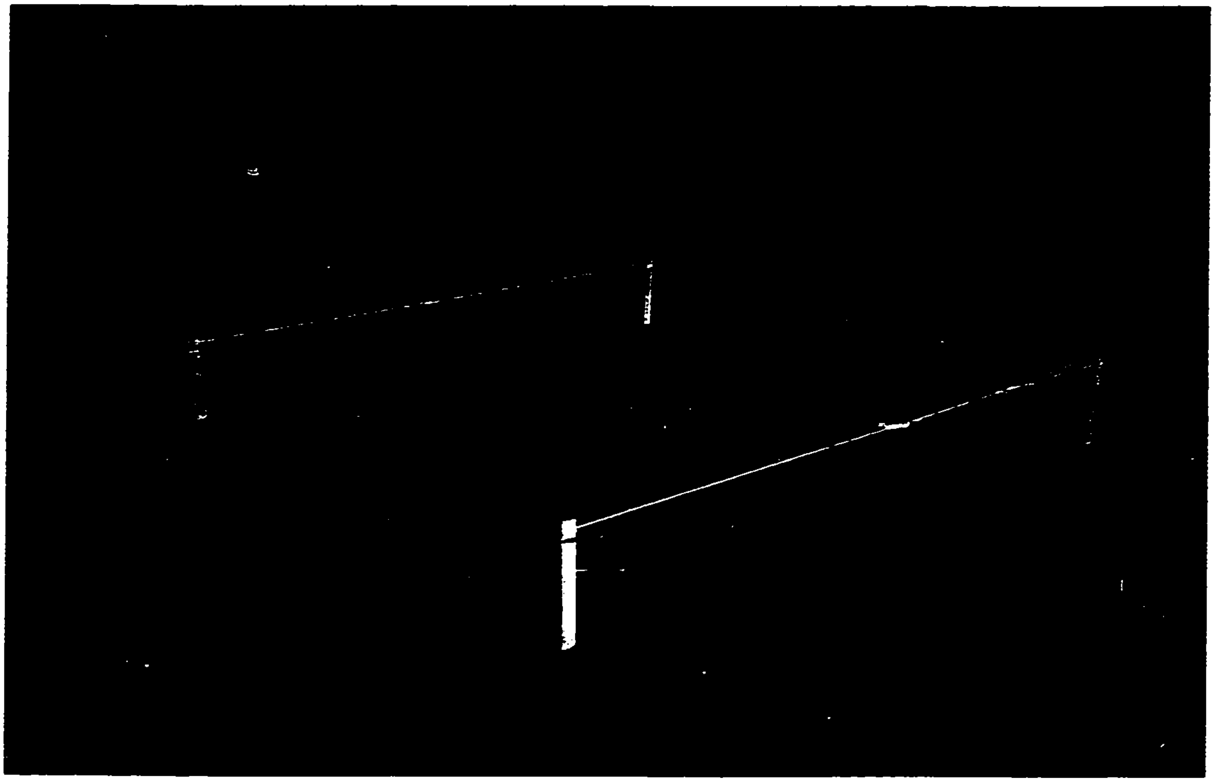


Figure 4.13 Plot of erosion pins near weather tower

flagged rope at a 25-30 cm height. From 12 December 1996 to 15 March 1997, there were two erosion pin plots in the study area: plot M was on the midbeach rise between the row of stakes and the sand-trap circle, and plot T was just north of the weather tower. The axis of each plot (through pins 2, 5, and 8) was oriented east-west.

Erosion pin heights were only measured when the beach was frozen and the surface could not be altered by the measurement process. Heights were taken to the nearest millimetre, and precision was controlled by always placing the metre-stick on the west side of the pins. Along with the date and time of the measurements, the surface condition of each plot was noted; on days when pin heights could not be measured, surface conditions were also noted (data-sheet EP-1 in appendix B). Changes in pin heights were directly related to elevation changes at the beach surface, that is, erosion or deposition. For each site and measurement interval, the minimum, maximum, and average erosion were calculated, compared between sites, and analysed with respect to the microclimate information and observed beach processes. The accuracy of erosion pin measurements is estimated at ±1.0 mm, with most of the possible errors from the measuring process. Passerby effects on the surface were negligible and wind modification by the ropes and corner stakes was minimized by plot orientation. The pins themselves showed little evidence of modifying the frozen ground; scour was never greater than 1 mm around the base of the pins--an order of magnitude less than the width of the metre-stick used for measurements.

4.5.4 Row of Stakes

Measurements of beach erosion were made on a larger scale by means of stakes placed in profile across the study area. Twenty-six of the 5x5x60 cm stakes were inserted at 3-metre intervals into the beach in a line with a 240° azimuth (figure 4.14). The stake heights were measured weekly with a metre-stick and surface conditions noted; the changes in stake height indicated erosion or deposition around the stake. Stake measurements, with an accuracy of ±1 cm, were not intended to be as accurate as erosion pin measurements because unnatural scour or deposition could and did occasionally occur at some of the stakes. Instead, the stake measurements gave a useful

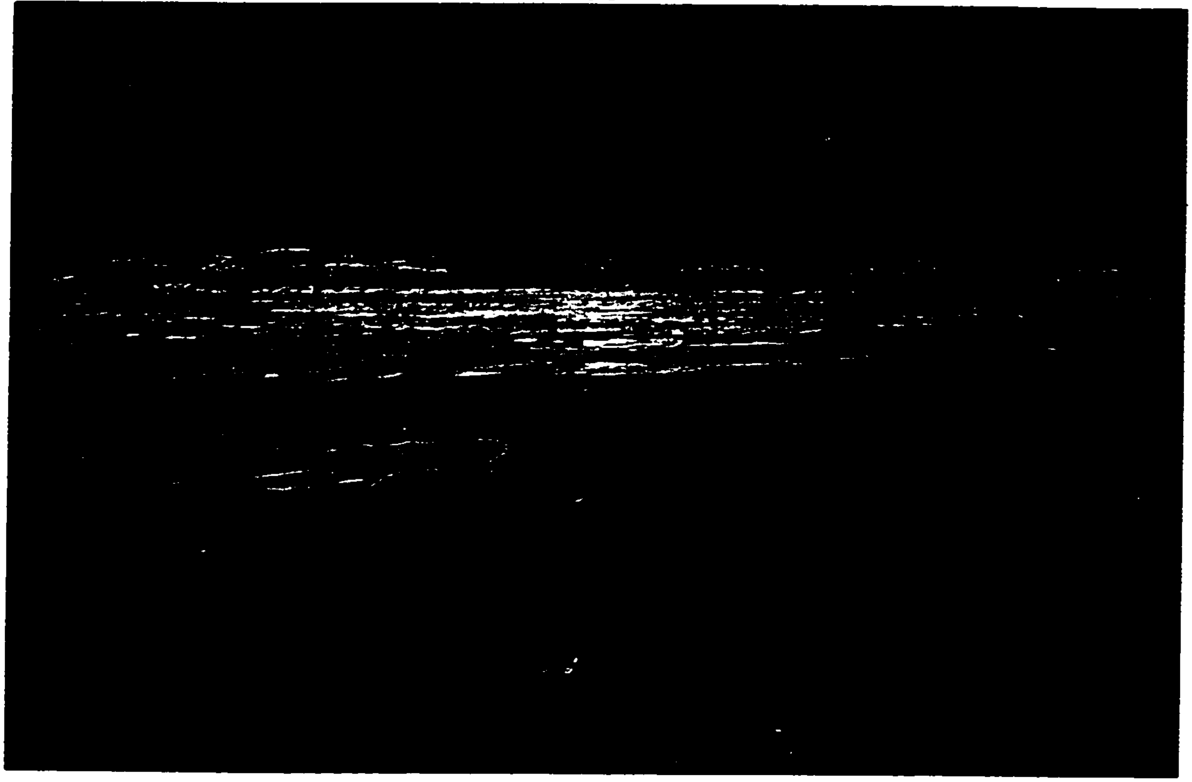


Figure 4.14 Row of stakes on Presqu'ile Beach

picture of general trends over the course of the winter. The stakes were also used as benchmarks for the beach observations and surface water content analysis.

4.5.5 Winter Sand Traps

When aeolian events occurred during the winter, winter sand traps captured moving sand to furnish quantitative data on amounts, rates and directions of movement. The vertical sand traps had 15-cm wide x 30-cm high apertures and rested on the beach surface; each was anchored by two wooden posts (1.5 cm in diameter) frozen into the beach. Commercially available pantyhose attached to the trap frame caught the moving sand but created minimal interference with the wind. A 4-metre diameter circle of wooden posts frozen into the beach served as 8 sets of trap anchors oriented at 45-degree intervals from north. The pantyhose-lined traps were clipped onto the posts at the start of each measurement period (figure 4.15). After a recorded time interval, the linings with trapped sand were detached and placed in labelled sample bags, and the traps were either reset or removed from the beach depending on whether sand movement continued. At the research station, the trapped sand was taken out of the liners and weighed; if snow was present, the sample was dried and weighed again to measure the quantities of snow and sand (data-sheet W-1 in appendix B). Totals of trapped sand and/or snow and rates of movement (grams/hour) were calculated by direction and time period, and the results analysed with respect to wind speed, wind direction, temperature, and the areal extent of exposed sand on the beach.

Figure 4.15 a) Circle of winter sand traps set out at Presqu'ile Beach and b) close-up of trap with captured sand and snow

4.5.6 Using Field Measurements to Test the Model

The 1996-1997 field measurements provided the real world data (and some of the inputs) needed to test the cold-aeolian model. Surface measurements of snow, ice cover, exposed sand, and soil water contents served, with microclimate measurements, as inputs to the model. From these inputs the model predicted whether or not sand would move, and how much would move. Model predictions of sand movement were compared to recorded observations of whether sand was actually moving. When aeolian activity did occur, erosion pin and sand trap data produced estimates of sand movement. These amounts were compared to model predictions for the same time period.

4.6 Spatial and Temporal Context

The context for the cold-aeolian model was examined at the Presqu'ile Beach study area. Numerous measurement sites in the study area established the spatial context for aeolian processes. At various locations erosion, deposition, surface cover and water content were recorded. Regular visits to the beach throughout the year placed the winter measurements into the context of annual changes. During the winter months, the occurrence and duration of warm events were recorded. By expanding the dataset spatially and temporally, the study established the importance of cold-aeolian processes to annual and long-term topographic changes.

Instead of concentrating on a narrowly-defined study site, field measurements purposely encompassed a substantial section at Presqu'ile Beach. The study area covered roughly 10 000 square metres and was bounded by Popham Bay to the west, a row of stakes to the south, the back of a foredune to the east and the edge of vegetation to the north. Point measurements of erosion and deposition were made along the row of stakes which were also used as benchmarks in visually assessing the extent of beach changes each day. Point measurements of surface water content covered numerous locations in the study area. Spatial estimates of various surface covers during the winter illustrated where aeolian deflation was or was not taking place.

The importance of winter processes to the annual sediment budget was assessed through regular observations of beach processes and change throughout the year. Within a single winter, cold and warm processes are interspersed. Intraseasonal variations in winter geomorphic processes were examined from daily beach observations and variations in temperature were extracted from microclimate measurements. These data were analysed with respect to significant conditions and processes during the winter months. Winter patterns of sediment movement and geomorphic processes were then compared to movement and processes during the three other seasons. Results were used to assess the importance of cold-aeolian activity to geomorphic change over the Presqu'ile beach and dune complex.

4.7 Summary of Methods

A diverse, sometimes unique, set of methods produced the results and cold-aeolian model of this dissertation. Table 4.4 summarizes the methods and shows how each one fits into the larger study. The underlying framework for the methods was the exercise of model-building. Each specific method was adopted or developed to solve a particular problem or need for information raised by the model-building process. A number of the questions posed in this cold-environment study are not typically asked in geography and required unusual techniques or innovative modifications to related methods. Thus, cementation and unconfined compression tests revealed characteristics of frozen surface resistance to aeolian entrainment, an improved sampler design permitted frozen surface water content to be measured, and winter sand traps captured sediment moving across the frozen beach.

stages of model-building	methods	results and discussion
1. Understanding the problem	literature review of relevant background material	chapter 3
	controlled-temperature experiments -visual observations -unconfined compression tests -cementation tests	chapter 5
	field experiments -sublimation experiments -moisture experiments -microclimate data	chapter 6
2. Constructing the model	defining variables and relationships	chapters 3, 5, 6
	computer generation of model	chapter 7
3. Testing the model	field measurements -beach observations -water content determination -erosion pins -stakes -winter sand traps -microclimate data	chapter 8
4. Using the model	establishing model context -beach observations -water content measurements -erosion measurements	chapter 9
	conclusions	chapter 10

Table 4.4 Summary of methods

Chapter Five

PORE-ICE COHESION AND AEOLIAN PROCESSES

> *There are lots of nice things you can do with sand;*
> *but do not try building a house on it.*
> C.S. Lewis

The freezing of moist soils limits the supply of sediment to aeolian processes. Resistance to entrainment is governed by pore-ice cohesion which is directly related to soil water content. Yet quantitative information on how specific water contents affect frozen-soil cohesion is simply not available. The objective of the controlled-temperature tests was to provide a quantitative classification of frozen sand that relates cohesion to water content, temperature and aeolian activity. In this chapter, the results of cementation tests and unconfined compression experiments are presented and then related to aeolian activity. Results of cementation tests allow specific water contents to be assigned to categories of frozen-sand cohesion. Results from unconfined compression tests explore temperature-dependent relationships between water content and cohesion. Aeolian activity is strongly linked to surface cohesion and different processes are observable at specific surface water contents.

5.1 Frozen Sand and Hodgson's Cementation Categories

177 prepared samples of frozen sand were tested according to Hodgson's (1974) criteria for cementation. Four sets of tests took place under 'warm' temperatures from -0.5°C to -2°C, one set had a 'moderate' temperature of -11°C, and the remaining four sets had 'cold' temperatures ranging from -16°C to -17°C. Sample water contents ranged from 0 to 19% by mass. Specified water contents were not the same for each test because appropriate values were being sought for the critical stages of cementation. The optimum specifications were 0.25% moisture differences from 0 to 3% followed by 2% moisture differences up to 19% (table 5.1). In reality, it was difficult to obtain the desired percentages because small amounts of water and sand were invariably 'lost' in the mixing process, despite extra water added during mixing to offset evaporation. The final water

contents used in the analysis (third column in table 5.1) were determined by oven-drying the sample after testing.

Table 5.2 summarizes test results by listing the lowest and highest water contents for each cementation category. Shaded numbers represent boundary conditions calculated by averaging the highest and lowest values from adjoining categories. The results have been divided into warm, moderate, and cold temperature groupings, and the boundary conditions have been averaged for each grouping (table 5.3). Because the boundary values are strongly influenced by variations in tested water contents, the group boundaries have been rounded to the nearest 0.5% moisture.

block #	calculated moisture (% mass)	actual moisture (% mass)
A	0.25	0.30
B	0.50	0.55
C	0.75	0.76
D	1.00	1.03
E	1.25	1.15
F	1.50	1.42
G	1.75	1.76
H	2.00	2.01
I	2.25	2.19
J	2.50	2.53
K	2.75	2.56
L	3.00	2.86
M	5.00	4.89
N	7.00	6.83
O	9.00	8.75
P	11.0	10.72
Q	13.0	12.93
R	15.0	14.89
S	17.0	16.78
T	19.0	18.75

Table 5.1 Specified and actual moisture contents for cementation test (CT) #14.

Test results clearly show that frozen sand cementation increases as water content increases. The frozen sand is uncemented at water contents from 0% to 0.5%. This range delineates loose sand in which small amounts of ice are not sufficient to bind sand grains to each other and have no significant effect on sediment characteristics. Above 0.5% water content, frozen sand is cohesive and the sand grains are rigidly held in position by interstitial ice. At these moisture levels, changes in cohesion are not visually distinctive and class names correspond to the results of the simple tests described in the second column of table 5.3. Low levels of cohesion which permit sample crushing in the hand extend from 0.5% to approximately 1.0%. Samples could be crushed underfoot

cementation categories	-2 deg C (CT#7)	-2 deg C (CT#8)	-1.5 deg (CT#9)	0.5 deg C (CT#10)		-11 deg C (CT#6)		-17 deg C (CT#11)	-17 deg C (CT#12)	16 deg C (CT#13)	-17 deg C (CT#14)
loose	0, 0.4	0, 0.3	0, 0.3	0, 0.4		0, 0.1		0, 0.3	0, 0.4	0, 0.4	0, 0.3
	0.6	0.4	0.4	0.5		0.4		0.4	0.4	0.5	0.4
very weak	0.8, 1.0	0.5, 0.9	0.6, 1.0	0.6, 1.2		0.6, 1.2		0.6, 0.8	0.5, 0.9	0.6, 1.0	0.6, 0.8
	1.1	1.0	1.1	1.4		1.3		0.9	1.0	1.0	0.9
weak	1.2, 2.7	1.2, 1.8	1.2, 1.8	1.5, 2.9		1.5		1.0, 1.9	1.0, 2.2	1.0, 1.5	1.0, 1.8
	2.8	2.0	1.9	4.0		1.7		2.0	2.3	1.6	1.9
strong	2.9, 16.1	2.2, 15.8	2.1, 18.1	5.9, 17.9		1.9, 9.7		2.1, 10.8	2.4, 10.8	1.8, 8.8	2.0, 6.8
	17.2	16.4	---	---		10.7		12.0	11.7	9.9	7.8
very strong	18.2	17.5	---	---		11.7, 17.7		13.1, 18.7	12.7, 18.7	10.9, 18.9	8.8, 18.8

Table 5.2 Water contents (in percent by mass) assigned to each category in cementation tests

class	description	warm boundary	moderate boundary	cold boundary
uncemented	loose sand	0	0	0
very weak cementation	cohesive but can be crushed by hand	0.5	0.5	0.5
weak cementation	can be crushed under foot but not by hand	1.0	1.5	1.0
strong cementation	can be crushed under a blow of 3 J but not underfoot	2.5	2.0	2.0
very strong cementation	cannot be crushed by a blow of 3 J	17.5	11.5	10.5

Table 5.3 Water contents (%) for lower boundaries of cementation classes

(under a weight of approximately 61 kilograms) to a maximum water content of 2.5%. Strong cementation begins at either 2.0% or 2.5%, and its onset demonstrates some temperature dependency. In other words, frozen sands require less pore-ice to become strongly cemented as temperatures decrease. The temperature dependency is even more obvious at the onset of very strong cementation which ranges from 10.5% at -16°C to 17.5% at -2°C.

5.2 Frozen Sand and Unconfined Compression Tests

In September and October 1995, unconfined compression tests were performed on 140 prepared samples of frozen sand. The reconstituted samples were composed of varying amounts of Presqu'ile Beach sand and distilled water. Each cylindrical sample had a nominal height of 10 cm and diameter of 4.2 cm. Sample dimensions and the height-to-diameter ratio of 2.4 lie well within American Society for Testing and Materials specifications (D2166-91, 1997). Visual observations of frozen-block cohesion with low water contents determined that the lowest water content used in testing should be 1.0%.

Equipment limitations set the maximum water content to be used in testing. Final water contents were determined by oven-drying the samples after testing; values ranged from 0.8% to 12.6% by mass. The results of four tests which exceeded equipment limits and one test in which maximum strain rate was not recorded were removed from subsequent analysis.

The cylindrical samples were frozen and tested in a controlled-temperature chamber. Nominal temperatures for the unconfined compression tests were -5°C, -8°C and -11°C, but the measured temperature oscillated throughout the experiment period. The thermostatically-controlled fan was triggered by temperatures several degrees above and below the chosen temperature. Furthermore, the control dial gave only rough indications of settings. Measured temperatures had averages of -4.6°C, -8.0°C and -10.9°C, respectively. Each sample was frozen for at least 11 hours at the test temperature before testing.

Relative humidity in the chamber could not be controlled. Measurements indicated that relative humidity ranged from 63% to 75% during the test periods. This narrow range of relative humidity did not significantly influence the experiment results.

The unconfined compressive strength (q_u) of each frozen sample was the compressive stress at which it failed in a simple compression test (American Society for Testing and Materials D2166-91 1997, 172). In each test, a sharp drop in measured load indicated failure and was usually accompanied by fracture of the test material. Compressive stress, σ_c, was calculated from

$$\sigma_C = (P/A) \qquad (5.1)$$

where P is the given applied load (ton/ft^2) and A is the corresponding average cross-sectional area (in.^{2}). Stress-strain curves and the abrupt rupture of the material indicated brittle failure, such as that found in concrete and rock when the material fails by separation (Nagaraj 1993). For frozen sands, brittle failure occurs above 10^{-4} s^{-1}

(Williams and Smith 1989, 252), and the average strain rate of these experiments was 1.2 x 10^{-4} s^{-1}. Shear strength (s_u) of the test specimens is calculated to be half the compressive strength at failure according to American Society for Testing and Materials D2166-91 (1997, 172).

5.2.1 Unconfined Compressive Strength and Water Content

Regression analysis shows a strong relationship between unconfined compressive strength and the water content of frozen sand (figure 5.1). For each test temperature, unconfined compressive strength increases as water content increases. The highest correlations were obtained when the natural logarithm of both compressive strength and water content were compared to each other. The intrinsically linear relationships (Devore 1987, 506) are best described by the power functions listed in table 5.4. High r^2's of 0.92 to 0.96 indicate that the relationships are very strong. Confidence intervals for q_u, with a significance of 0.05, are listed in table 5.4 and graphically represented in figure 5.2.

temperature	observations	equations	ϵ p=0.05	r
-5°C	58	$q_u = 0.18\omega^{1.01} \cdot \epsilon$	±0.25	0.94
-8°C	38	$q_u = 0.29\omega^{1.01} \cdot \epsilon$	±0.23	0.96
-11°C	42	$q_u = 0.32\omega^{1.14} \cdot \epsilon$	±0.46	0.92

Table 5.4 Equations for unconfined compressive strength (q_u) as a function of total water content (ω)

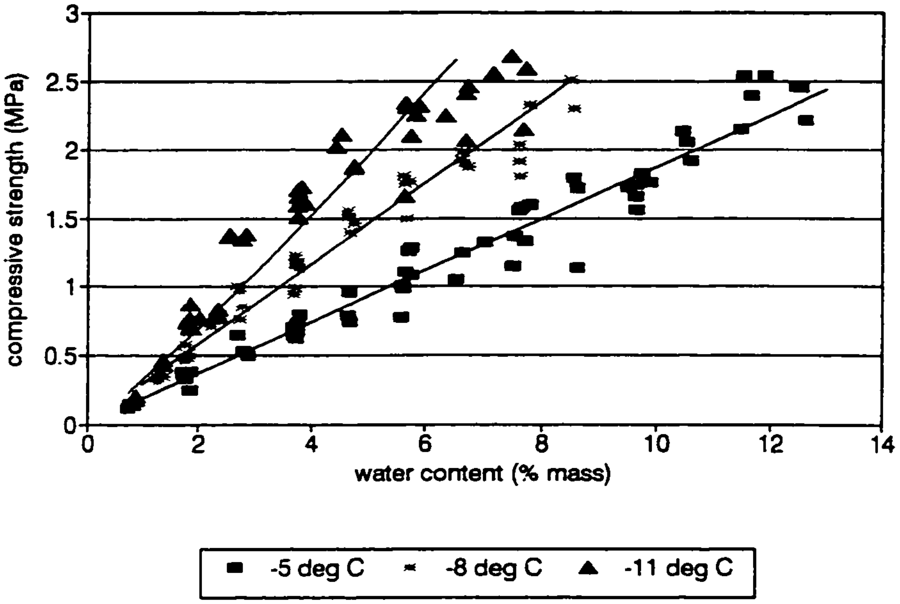


Figure 5.1 Unconfined compressive strength with frozen-sand water content at -5°C ($r^2=0.98$), -8°C ($r^2=0.96$) and -11°C ($r^2=0.92$)

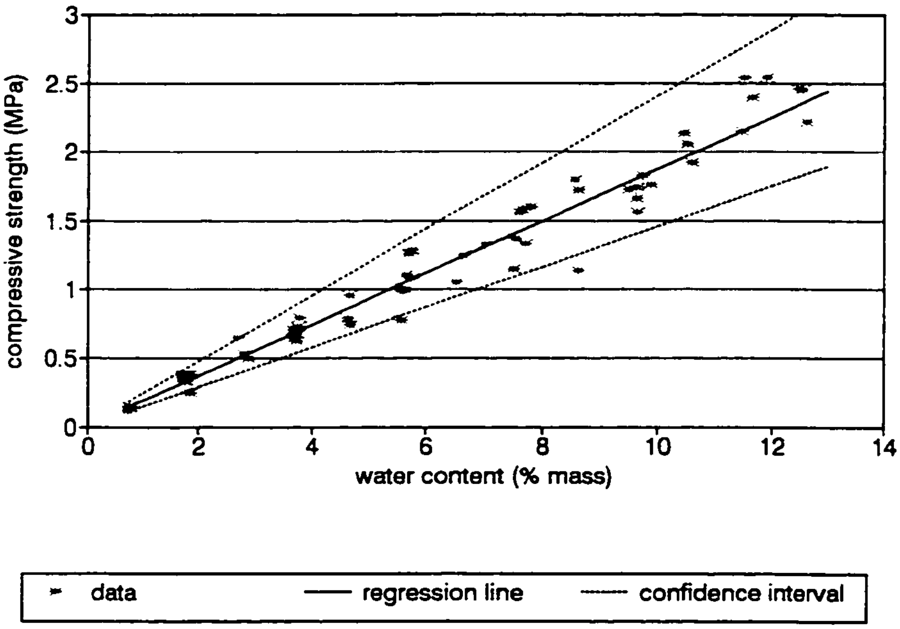


Figure 5.2 Relationship (with confidence intervals) between unconfined compressive strength and water content at -5°C ($r^2=0.98$)

5.2.2 Unconfined Compressive Strength and Temperature

Regression analysis shows a strong relationship between unconfined compressive strength and temperature. As temperature decreases, there is a significant increase in the unconfined compressive strengths of samples with similar water contents (figure 5.3). The increase in sample strength results from the stronger ice bonds at lower temperatures. The strong relationships between temperature and strength are described by the linear functions listed in table 5.5. The confidence intervals for samples with 4% water content are depicted graphically in figure 5.4. The 95% confidence intervals and values for r^2 reflect the lower number of observations and degrees of freedom for the tests with similar water contents. Measured water contents as much as 0.2% above or below the average value may account for some of the decreased accuracy.

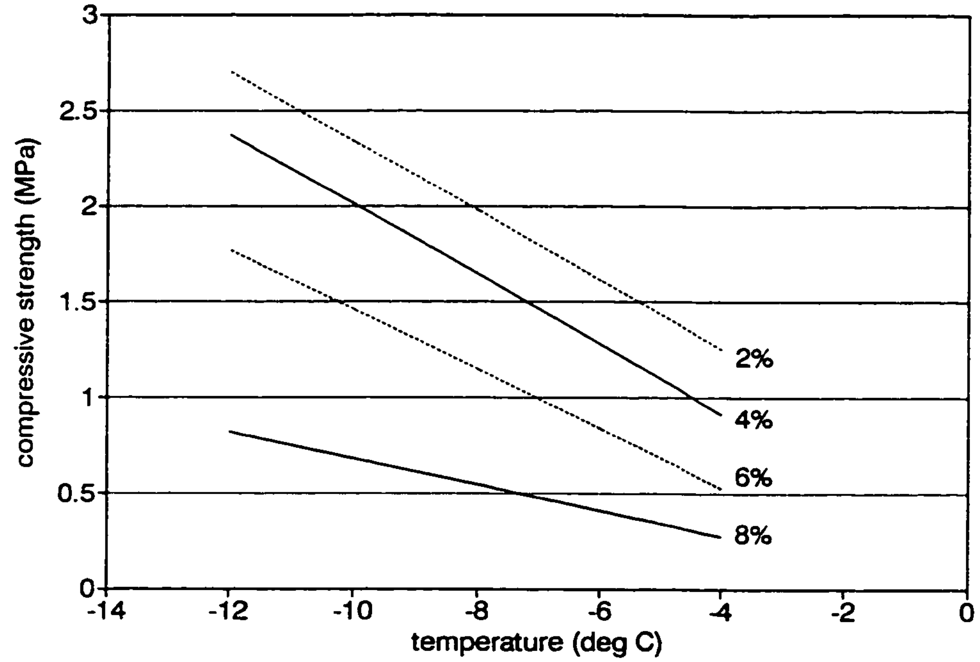


Figure 5.3 Unconfined compressive strength and temperature for samples with 2% (r^2=0.92), 4% (r^2=0.96), 6% (r^2=0.86), and 8% (r^2=0.86) water

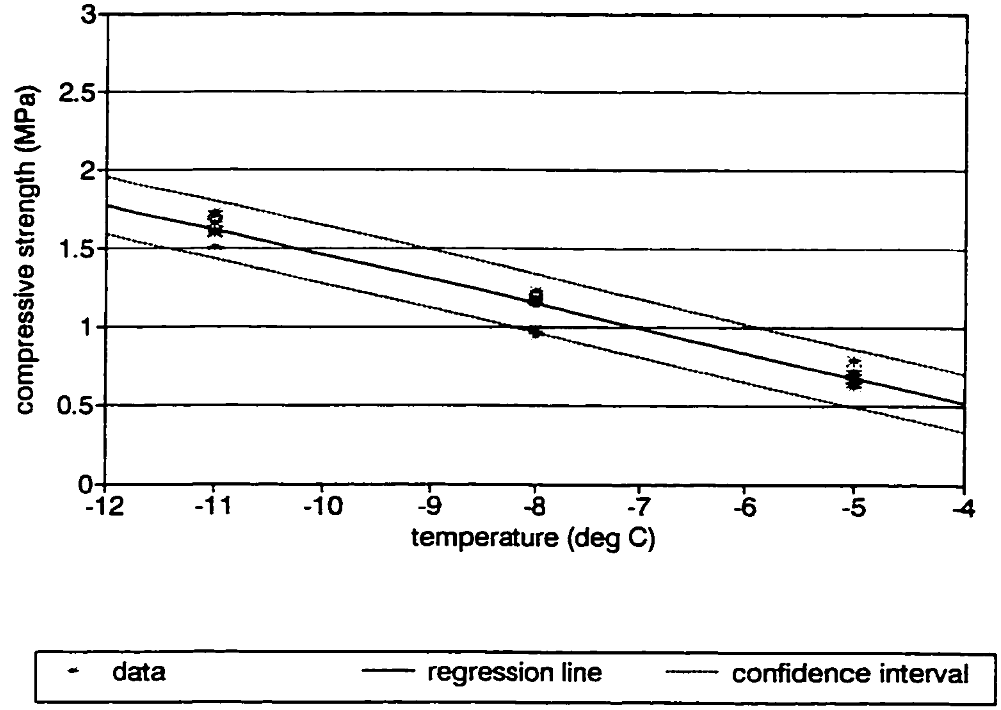


Figure 5.4 Unconfined compressive strength of frozen sand (4% water content) with temperature ($r^2=0.96$)

average water content	observations	equation	ϵ ($p=0.05$)	r^2
1.8 %	17	$q_u = -0.07\theta + \epsilon$	± 0.12	0.92
3.7 %	19	$q_u = -0.16\theta - 0.10 + \epsilon$	± 0.18	0.96
5.7 %	17	$q_u = -0.18\theta + 0.18 + \epsilon$	± 0.43	0.85
7.7 %	14	$q_u = -0.18\theta + 0.52 + \epsilon$	± 0.42	0.79

Table 5.5 Equations for unconfined compressive strength q_u with temperature θ; error terms indicate the 95% confidence interval

5.2.3 Unconfined Compressive Strength and Cohesion

Strength is the maximum resistance of a material to applied stress (Williams and Smith 1989, 243). In dry particulate matter, strength depends on two quantities--cohesion and friction--which are related in the Mohr-Coulomb equation (Williams and Smith 1989):

$$\tau = C + \sigma \tan\phi \tag{5.2}$$

where τ = shear stress at failure,

C = cohesion

σ = normal stress at failure, and

ϕ = friction angle.

In dry sands, cohesion is negligible and the frictional component dominates soil strength. The shear resistance of the particles with respect to each other produces the friction which increases as the confining stress increases (Williams and Smith 1989).

When water freezes in sands, soil strength increases because of bonding between the mineral particles and ice crystals. The frictional component of frozen soil strength is attributed to soil particles with minor contributions by some fractured ice crystals (Williams and Smith 1989, 244). Pore-ice bonding does not change the frictional component because "the addition of a cementing agent to cohesionless material results in an enhancement of only the cohesion component" (Aiban 1994, 72). The cementing agent of frozen sand is interstitial ice which forms the cohesion component of strength. Because the frictional component of strength remains constant, changes in frozen sand strength represent changes in the cohesion component. When the ice fraction, or cohesion component, tends to zero, "the strength of an unsaturated frozen sand decreases rapidly to that for a dry sand" (Ladanyi 1981, 213). Variations in frozen sand strength resulting from changes in temperature or water content can be used to study changes in cohesion.

Strength reflects cohesion, and unconfined compression tests reveal characteristics of the relationship between cohesion and the water content of frozen sand at different temperatures. High values for r^2 point to a strong relationship between cohesion and total water content. The experiments indicate that cohesion increases as a power function of water content. Furthermore, this relationship is temperature-dependent. The increased strength of ice bonds at lower temperatures produces increased cohesion. The temperature-dependent increase in cohesion with water content has important implications for aeolian activity.

5.3 Pore-Ice Cohesion and Aeolian Processes

When frozen sands are exposed to wind, pore-ice cohesion increases the resistance of surface particles to aeolian entrainment. Both fluid and impact entrainment are affected, although the outcomes are different for each mode of entrainment. The relationship between water content and cohesion sheds light on how pore-ice cohesion affects entrainment by wind.

5.3.1 Fluid Entrainment and Pore-Ice Cohesion

Fluid entrainment occurs when the forces of the wind overcome a soil particle's resistance to movement. Pore-ice cohesion interferes with this process by increasing the particle's resistance to movement. The interaction between cohesion and fluid entrainment is marked by two critical points. The first is the boundary between loose and cohesive sand. This level of cohesion, which corresponds to a specific water content, marks the division between "archetypal" fluid entrainment and cohesion-limited fluid entrainment. The second critical point occurs when it is no longer possible for the forces of wind alone to overcome the resistance of cemented grains. Also corresponding to a specific water content, this level of cohesion marks the division between fluid entrainment influenced by cohesion and fluid entrainment prevented by cohesion. Three distinct phases are delineated by these boundaries: archetypal fluid entrainment, cohesion-limited fluid entrainment, and no fluid entrainment.

5.3.1.1 Uncemented Sand

Fluid entrainment is not significantly affected by pore-ice cohesion when the frozen surface remains uncemented. If small amounts of ice, but not enough to hold grains together, are present in the pore spaces, they will have no apparent influence on fluid entrainment. Ice which is attached to individual grains will be entrained with them and quickly sublimate during saltation. Ice which has filled the occasional pore space may prevent one or several grains from moving briefly, but surrounding less-resistant grains will be entrained instead. When the wind is strong enough to remove particles from the surface, it is also strong enough to quickly dry any remaining pore-ice.

Under cold temperatures, archetypal fluid entrainment is limited to frozen sands which are not cemented. This category includes dry frozen sand (0% water content), and frozen sands with water contents up to 0.5%. At these low water contents, pore-ice is unable to bind sand grains together and has no significant effect on direct entrainment by wind. Above 0.5%, frozen sands are cohesive and less likely to be moved by wind.

5.3.1.2 Immobilized Sand

Pore-ice cohesion makes fluid entrainment impossible when the frozen sand is firmly cemented. The interstitial ice binds the grains together so strongly that the wind does not have the force to break the grains free. On the north shore of Lake Superior, Marsh and Marsh (1987, 387) saw that "no grain movement can occur until the frost (ice) itself frees the grain", and Miotke (1984, 46) confirmed that "wind velocity plays no significant role since the bonding is too strong" in the Antarctic. The solution, in both cases, is pore-ice sublimation which frees the grains and lowers their resistance to movement.

Pore-ice cohesion quickly increases with water content, and levels of 1% water content and above are sufficient to prevent direct entrainment of surface grains. At 1% water content, frozen sands have enough cohesion to resist applied forces of up to 80 newtons. With respect to aeolian processes, the label 'weakly cemented' is a misnomer--these sands have many times the cohesion of unfrozen wet sands upon which movement is impossible above 5% moisture (Nickling 1994). At this level of cohesion particles cannot be fluidly entrained until the surface itself frees the grains through pore-ice sublimation.

5.3.1.3 The Transition Zone

In the transitional phase between archetypal entrainment and immobilized grains, pore ice begins to have noticeable effects on entrainment. Surface grains increase their resistance to movement and require stronger winds to pluck them from their resting places. Threshold velocities must increase as surface cohesion increases.

The limits of this transitional phase have been assigned as residual values from the two neighbouring phases. Thus, cohesion influences fluid entrainment when surface water contents range from 0.5% to 1.0%. The upper limit of 1.0% may be quite generous because testing demonstrated that considerable force is already needed to overcome cementation at this level.

Within this range of water contents, threshold velocity increases as more or stronger interstitial ice develops around sand grains. The relationship between threshold velocity and cohesion is difficult to measure and remains unknown. In comparable studies of cementation resulting from soluble salts, threshold shear velocity increased linearly with salt concentrations (Nickling and Ecclestone 1981; Nickling 1984). Studies on unfrozen damp surfaces found an exponential increase in threshold shear velocity with moisture content (Chepil 1956; Belly 1964; Azizov 1977). Given the small range of water contents involved, a linear increase in threshold velocity will be assumed for modelling purposes in this dissertation. Specific studies are needed to address this question in the future.

5.3.2 Abrasion, Entrainment and Pore-Ice Cohesion

When interparticle cements are really strong, entrainment only occurs when pieces are chipped off the hard surface in the process of abrasion (Warren 1979, 328). The success of abrasion depends on the energy of the impacting particle and the resistance of the abraded surface. Pore-ice cohesion, which increases particle resistance, influences the possibility and rate of entrainment by impact. Characteristics of impact entrainment depend on whether or not the frozen sand is cemented.

5.3.2.1 Impact on Uncemented Frozen Sands

Particles can be entrained from a bed of loose grains during impacts between moving grains and the bed. In a typical collision, the saltating grain strikes the bed at an angle between 10-16° and ricochets into the air at an angle between 20-40°, keeping about 60% of its impact speed (McEwan, Willetts and Rice 1992, 972). One or more grains, with speeds an order of magnitude less than the impact grain, may be ejected from the bed. The remainder of the impact grain's momentum is lost in lateral movement among the bed grains (McEwan, Willetts and Rice 1992, 979). Grains in motion gain momentum as they are accelerated by the wind. Impact entrainment allows saltation to be maintained at lower wind velocities than are necessary for fluid entrainment--the impact threshold is commonly assumed to be 80% of the fluid entrainment threshold (after Bagnold 1941).

For frozen sands, the description of impacts on a loose bed applies when the surface has a water content between 0% and 0.5%. Tiny bits of ice which may be present at the upper end of the water content range can easily be entrained with the larger sand grains, and quickly sublimate as they move through the air. Changes in temperature have no significant effects on the characteristics of the surface. Threshold velocities do decrease as temperatures decrease because air density varies inversely with temperature (McKenna Neuman 1993).

5.3.2.2 Impact on Cemented Frozen Sands

Cemented frozen sands change the nature of grain-bed impacts. The rigid surface structure causes elastic collisions and enables ricocheting grains to retain a larger portion of their momentum. Unlike interactions on a loose bed, the ice cement does not permit many small lateral movements of grains, and momentum remains with the moving particles. The elastic grain-bed interactions produce higher saltation trajectories and carry the grains further than on loose surfaces.

Particle entrainment during grain-bed impacts on cemented surfaces is made possible through abrasion. The impacts can remove surface grains from the cementing agent and propel them into saltation. Abrasive erosion is described by

$$W = f(V_p^c, d_p^b, \alpha, S_a) \tag{5.3}$$

where W is abrasive erosion, v_p is the abrading particle's velocity, d_p is particle diameter, α is angle of impact, S_a is aggregate stability, and c and b are constants (Hagen 1984, 807). Particle velocity depends on wind speed over the surface, and under natural conditions can range from 25-800 cm s^{-1} (Haff and Anderson 1993, 187). Hagen (1984, 808) suggests that optimum impact angle for abrasion is 30°, but saltation usually produces impact angles between 10° and 16° (McEwan, Willetts and Rice 1992).

The aggregate stability term (S_a) in equation 5.3 has been described as crust, rock or surface strength, depending on the context. The importance of this term to the equation is that the resistance of the abraded surface affects erosion by impact. Surface resistance has been measured in different ways on different surfaces (table 5.6), and comparison is difficult. Researchers generally agree, however, that abrasion is inversely proportional to the strength (stability) of the abraded surface. The most effective mechanism of abrasion is the separation of grains, rather than the destruction of the grain itself (Suzuki and Takahashi 1981, 26).

Frozen soil strength increases with water content, and abrasion, therefore, will be inversely proportional to frozen soil water content. Although surface strength was not directly measured, wind tunnel experiments by McKenna Neuman (1989) demonstrated that frozen soil surfaces do become more stable at greater moisture contents. Percentages of ejected to total number of grains in motion decreased as water contents increased (table 5.7). In the present study, abrasion was not measured but tests on frozen sand confirmed that strength is directly proportional to water content.

Study	abrasion surface	measure of surface resistance
Dietrich (1977)	fluorite, halite, periclase, sylvite	abrasion by dust in wind tunnel
Suzuki and Takahashi (1981)	various rocks	unconfined compressive strengths, tensile strengths
Gillette *et al.* (1982)	surface crusts	modulus of rupture
Hagen (1984)	soil aggregates	drop test
McKenna Neuman (1989)	frozen spheres	abrasion by spheres in wind tunnel
Zobeck (1991)	surface crusts	abrasion by sand particles in wind tunnel
Rice, Willetts and McKewan (1996)	surface crusts	punch strength (flat-ended cylindrical penetrometer)

Table 5.6 Different ways surface resistance to abrasion has been measured

volumetric water content	percent ejected/total particles in motion at temperatures -5°C	-10°C	-22°C	comparable water content by mass for Presqu'ile Beach sand
11-20	40.4	34.1	66.7	7-13
21-30	18.9	13.9	38.3	14-20
31-40	9.2	5.6	26.9	20-26

Table 5.7 Percentage of grains in saltation from impact entrainment; figures in columns one and two are from McKenna Neuman (1989, 1011)

Abrasion of frozen sand is influenced by frozen-sediment temperature. The present study demonstrates that cohesion increases as temperature drops. McKenna Neuman (1989) also found that susceptibility to entrainment by impact decreased as temperatures dropped. Below -20°C, the frozen surfaces become brittle and are less stable with respect to impacts and abrasion (McKenna Neuman 1989). In fact, the greatest percentage of grains were ejected by impact at -22°C. McKenna Neuman (1989, 1013) attributes the increase in ejection to the reduced mobility of hydrogen atoms in the crystal lattice with corresponding reductions in ductility and rate of strength increase.

Frozen sand cohesion becomes important to grain-bed impacts at approximately 0.5% water content. Just above this boundary, impacts can be expected to push considerable amounts of material into saltation. The amount of abraded material varies inversely with frozen soil water content, and frozen sands with high water contents will have much smaller amounts of material entrained through abrasion. As fewer particles break away from the surface, collisions retain more energy in the moving grains, and saltating particles jump higher and travel further.

It is important to note that pore-ice cementation does not have the same effect as crusts created by soluble salts and algae. Surface crusts are firmly held together by the cementing agent (salts, algae) and protect underlying loose sand. When the crust undergoes abrasion and breaks up, the underlying sand is exposed and an immediate increase in sand transport can be observed. The pattern for transport points to initial supply limitations (wind carries much less sand than it could) followed by a gradual increase to non-supply-limited transport. Frozen sands do not exhibit the same increase in transport with time. Transport remains limited by frozen surface cohesion, and abrasion simply exposes more cemented sand.

5.5 Sublimation, Entrainment and Pore-Ice Cohesion

On cemented frozen sands, sublimation is the bridge between the impossibility of fluid entrainment and the activity of impact entrainment. When winds are unable to directly (and fluidly) entrain grains from the frozen surface, pore-ice sublimation releases particles which are entrainable. This action makes downwind abrasion of frozen cemented sands possible. Indirectly, sublimation controls the abrasion rate by controlling the amount of particles which will impact the surface. The net result is that sublimation controls the transport rate. The interaction between sublimation and pore-ice cohesion is discussed in more detail in the next chapter.

5.6 Moisture-Based Classification of Frozen Sand

The information outlined in this chapter can be combined into a comprehensive moisture-based classification for frozen sands (table 5.8). The classification assigns specific water contents as boundaries for frozen sand cohesion, fluid entrainment, and elastic impacts. The critical boundary at 0.5% water content separates frozen sands with insignificant cohesion from those with significant cohesion. This border separates unmodified fluid and impact entrainment from modified entrainment and elastic impacts. As water contents increase above this critical level, cohesion increases, fluid entrainment is no longer possible, and fewer particles are released from the surface through abrasion. Temperature effects are noted at the bottom of relevant columns in table 5.8. Most of the changes involve gradual strengthening of cohesion with decreasing temperatures, but the sharp change to brittle bonds near -20°C has notable consequences for surface abrasion.

5.7 Summary

Controlled-temperature experiments demonstrate that frozen-sediment cohesion is directly related to water content. The experiments indicate ranges of water contents for different categories of frozen-sand cohesion. These data are unprecedented in relating specific water contents to the description of frozen sand. Experiments have also shown that the relationship between cohesion and water content takes the shape of a power function. Cohesion increases exponentially as the water content of the frozen sand increases.

The quantitative description of cohesion is important to the study of aeolian processes on frozen sands. Some boundaries between different classes of cohesion correspond to

class	description	water content (%)	entrainment (fluid)	threshold	grain impacts
uncemented	loose sand	0 0.5	possible	no change	no change
very weak cementation	cohesive but can be crushed by hand	0.5 1.0	possible	increases with water content	elastic collisions with surface; decreasing number of grains detached from surface as water content increases
weak cementation	can be crushed under foot but not by hand	1.0 2.0	not possible		
strong cementation	can be crushed under a blow of 3 J but not under foot	2.0 10.5	not possible		
very strong cementation	cannot be crushed by a blow of 3 J	10.5 saturated	not possible		
effects of temperature		as temperature increases the water content for onset of strong and very strong cementation increase	as temperatures decrease, thresholds increase		as temperatures decrease released particles decrease; at -20 deg C and below, more grains are released because surface is brittle

Table 5.9 Moisture-based classification of frozen sands

distinct changes in sediment entrainment mechanisms and impacts of saltating grains on the surface. The new classification for frozen sands (table 5.8) enables differentiation between types of aeolian activity based on simple measurements of surface water content. Uninhibited aeolian activity occurs on only the driest frozen sands. Where frozen sands exceed these low water contents--for example, many temperate, coastal beaches and dunes--aeolian activity is significantly influenced by pore-ice cohesion.

Chapter Six

SAND SUPPLY TO COLD-AEOLIAN PROCESSES

> *The night is darkening round me,*
> *The wild winds coldly blow;*
> *But a tyrant spell has bound me*
> *And I cannot, cannot go...*
> Emily Brontë

The primary mechanism for supplying loose sand to cold-aeolian processes is pore-ice sublimation. As the frozen surface dries by sublimation, grains are released from the influences of pore-ice cohesion. The rate of particle release is controlled by local conditions of wind speed, temperature, relative humidity and surface water content (van Dijk and Law 1995).

The objective of semi-controlled field experiments was to produce an equation in which local conditions predict the amount of sediment released from a frozen surface. In this chapter, results from two sets of experiments are described and analysed with respect to sublimation-induced particle release. In the first experiment, frozen sand blocks were exposed to a variety of natural conditions and sediment losses were compared. In the other experiment, frozen sand blocks with different water contents were exposed to identical field conditions and sediment losses were compared. Results from both experiments are combined to predict the aeolian supply of sand from a frozen surface.

6.1 Field Experiment Results

Field experiments to measure sand loss from frozen surfaces were carried out during the winter months of 1996 and 1997. The design, equipment and location of the experiments have been described in chapter four. On 63 nights, two trays of prepared frozen sand blocks (nominal water contents of 6%, 8% and 10%) were exposed to beach conditions for 12 hours. The results from 25 of those nights were taken out of the data-set for the following reasons: significantly different location of blocks on the beach (14 nights), block surfaces significantly above the level of the beach surface (3 nights), temperatures above 0°C for part of the night (2 nights), overnight snowfall covered the blocks (2 nights), blown snow covered the blocks (2 nights), and frost formed on blocks (2 nights). The remaining 38 nights of data were used in the analysis of surface sand loss.

A representative range of temperatures, humidity, and wind speeds were recorded during the 38 experiment periods. Average temperatures fluctuated between -0.1°C and -18.4°C (figure 6.1). Relative humidity ranged from 43% to 84% with most of the experiments

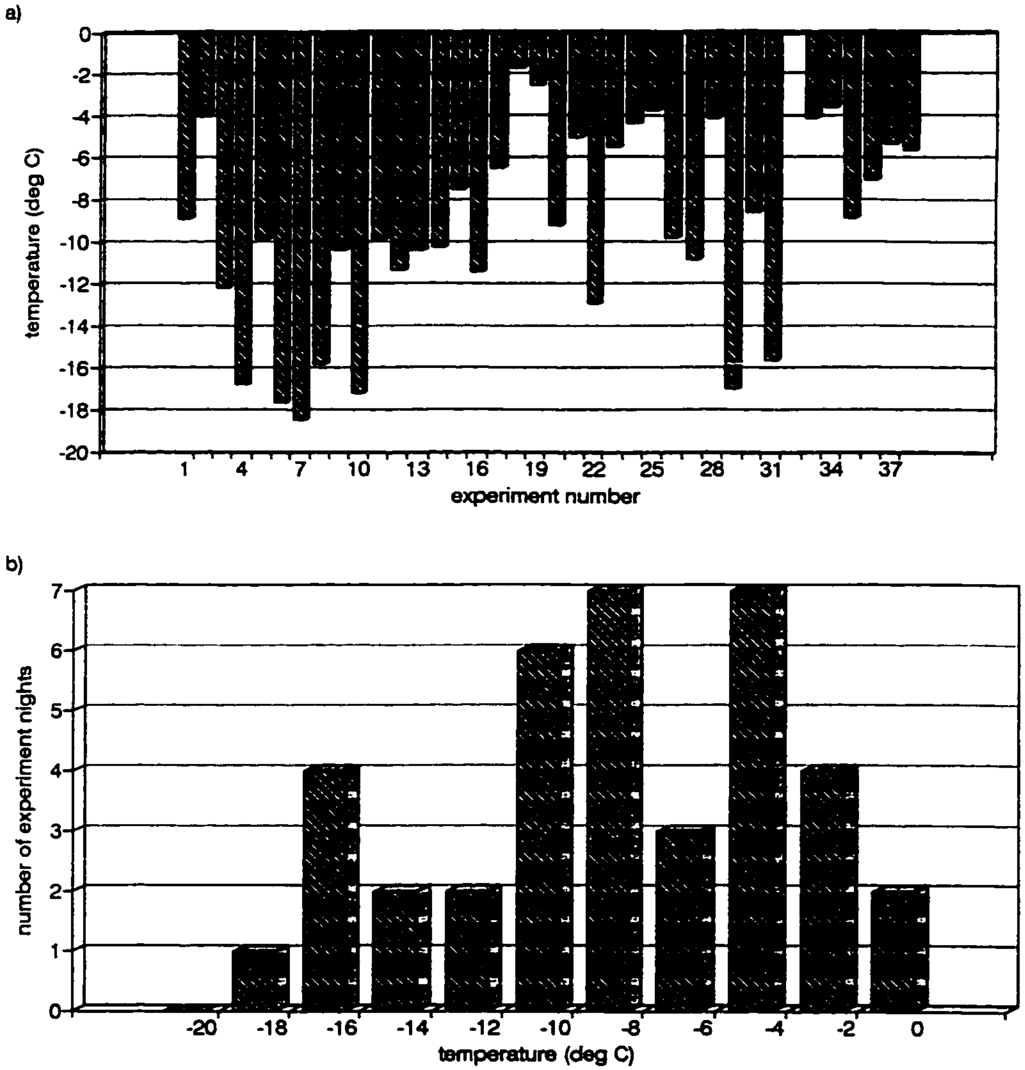


Figure 6.1 Air temperatures (12-hour averages) for experiments shown a) by experiment night and b) as a frequency distribution

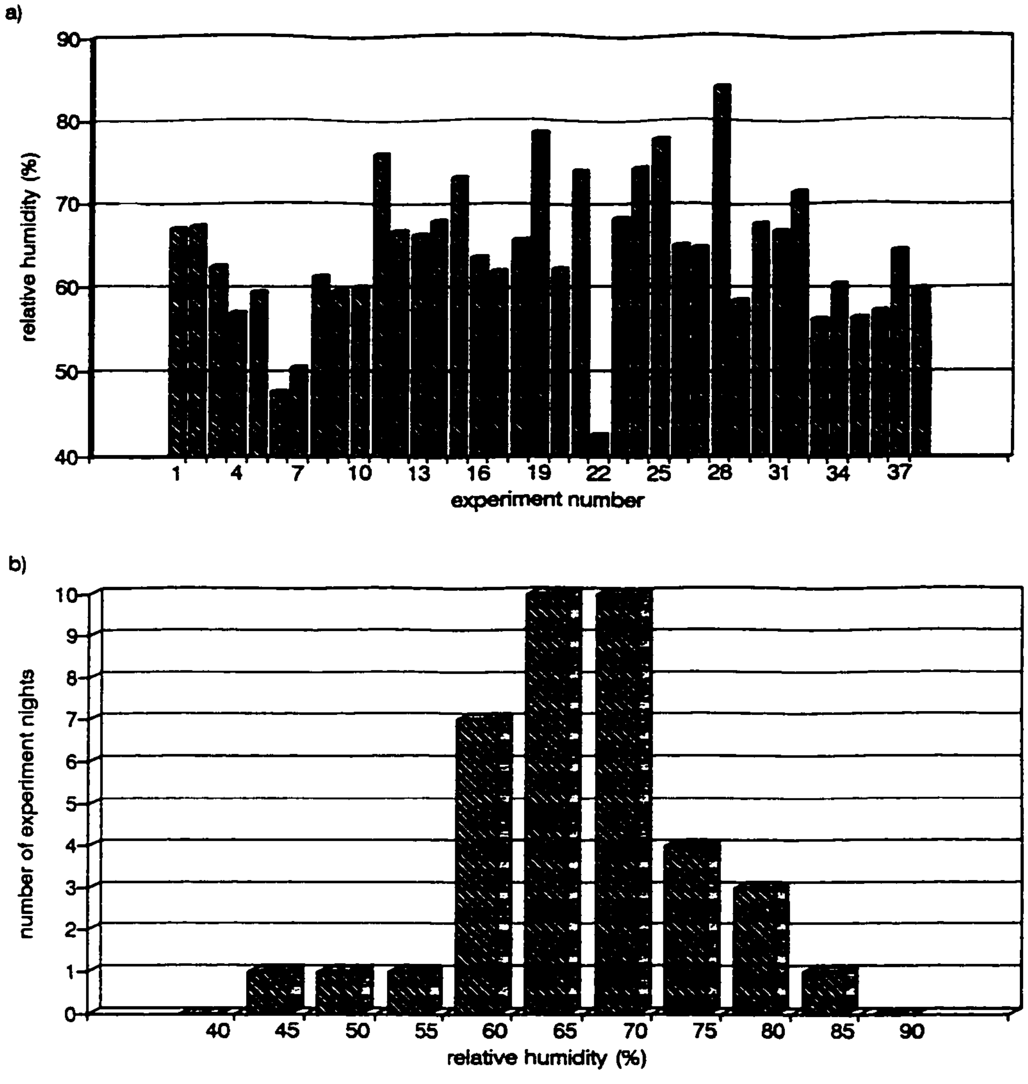


Figure 6.2 Relative humidity (12-hour averages) for experiments shown a) by experiment night and b) as a frequency distribution

lying between 60% and 70% (figure 6.2). Average wind speeds measured at 6 metres above the beach surface varied between 1.2 m/s and 9.7 m/s for the 12-hour periods (figure 6.3). On 18 of the nights, sand movement across the beach was observed; blowing snow accompanied the sand on three of those nights and blowing snow only was observed on two other occasions. Light snowfall or flurry action occurred on 12 of the experiment nights.

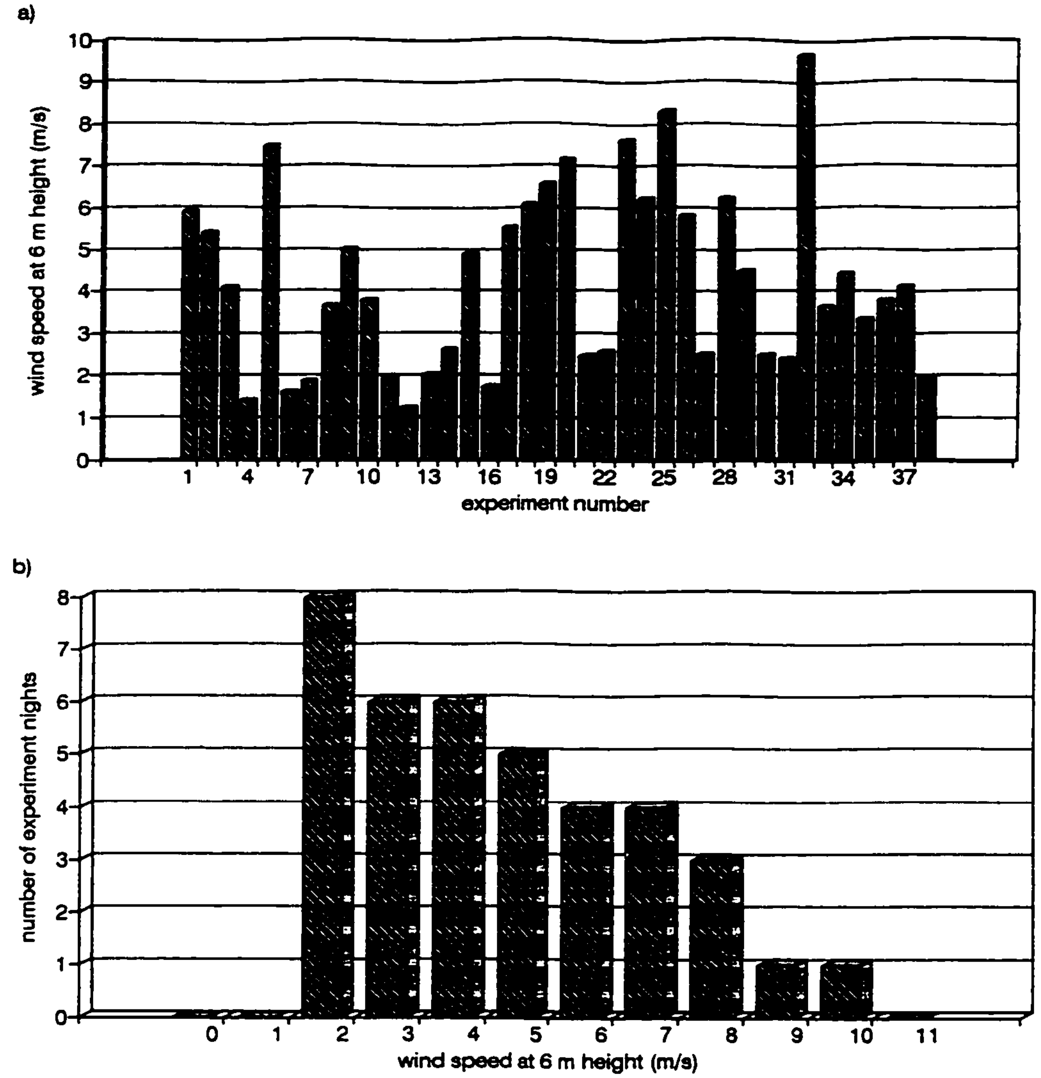


Figure 6.3 Wind speeds (12-hour averages at 6 metres) shown a) by experiment night and b) as a frequency distribution

Wind directions on experiment nights reflect the local pattern of frequent onshore winds from the west (figure 6.4). During less frequent events the winds come from the opposite direction and blow offshore. The distribution of Presqu'ile winds is typically bimodal with a second peak near 60 degrees from north (van Dijk 1993, 75). Figure 6.4 shows the beginning of a weak second peak from 60° to 180°. Wind direction had some bearing on experimental results in that the greatest sand losses were measured from

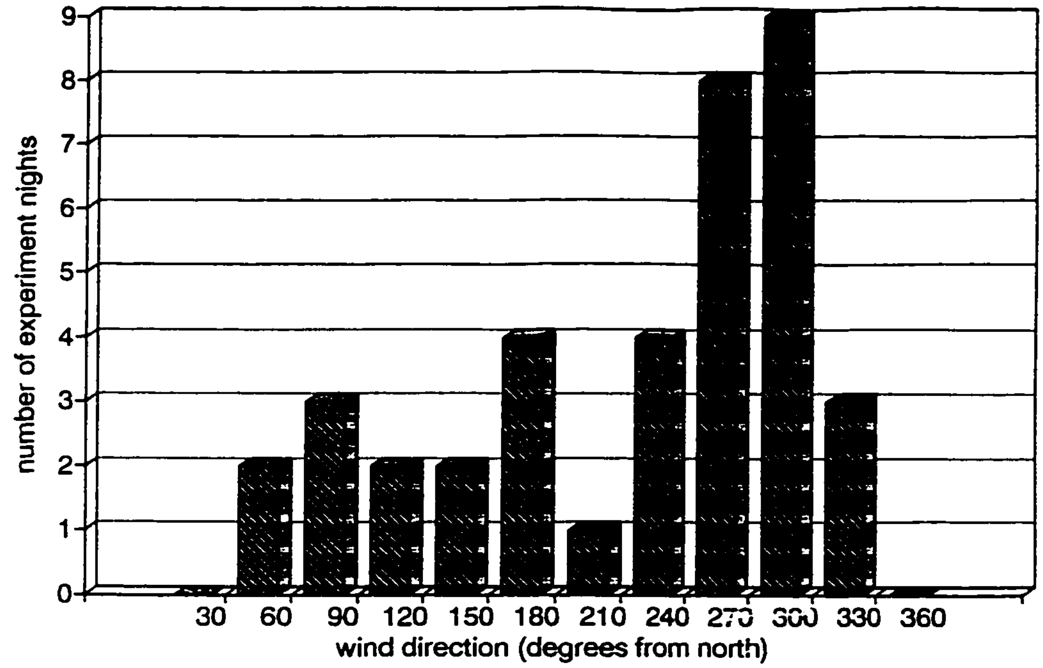


Figure 6.4 Frequency distribution of wind directions (12-hour averages) for Presqu'ile beach during experiment nights

windward blocks. To correct for these effects in the analysis, block designations were reversed when the average wind direction lay between 315 and 135 degrees (figure 6.5). Corrections were made for 7 of the 38 experiment nights. Experiment results that are reported by block position are the corrected results.

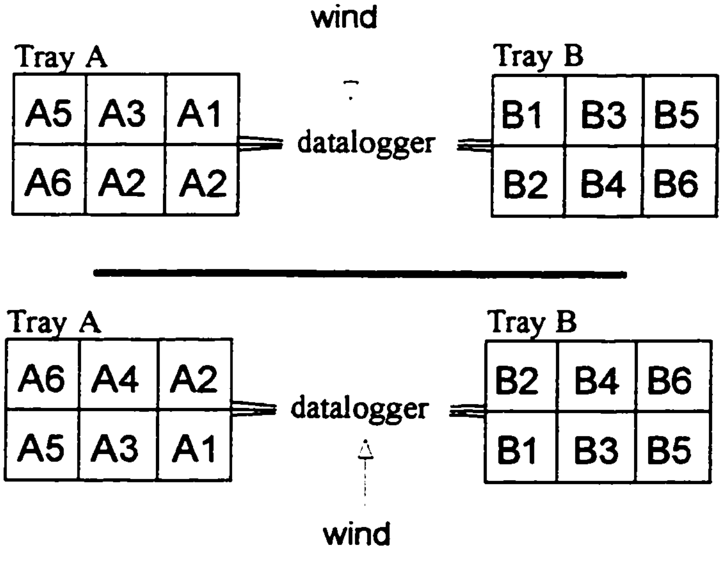


Figure 6.5 Corrected block positions to offset wind direction effects

% water	average	minimum (date)	maximum (date)
6 %	25.1 g	3.0 g (14 Feb 96)	86.6 g (19 Dec 96)
8 %	16.2 g	1.3 g (14 Feb 96)	63.3 g (19 Dec 96)
10 %	12.1 g	0.7 g (14 Feb 96)	41.1 g (29 Feb 96)

Table 6.1 Sand losses from frozen test blocks during Presqu'ile field experiments

Sand losses from the frozen test blocks over the 38 experiment nights are summarized in table 6.1. Losses ranged from a low 0.7 grams for a 10% block set out on a night with extremely low wind speeds and moderately low temperatures to a high of 86.6 grams for a 6% block set out on a night with very high winds and moderately warm temperatures. Block water contents, measured after each test, had averages of 5.8%, 7.9% and 9.8% which were slightly below the nominal levels of 6%, 8% and 10%, respectively.

Over the 38 experiment nights a total of 2914.8 g of sand were removed from blocks set out in tray A (8% water) and 3081.4 g of sand were removed from the blocks in tray B (6%, 8%, and 10% water contents). The total weight loss from the blocks in the two trays would correspond to 28.4 kg of sand lost from one square metre of beach during the same time period under the same conditions. That amount represents a substantial sand supply for aeolian processes. Measured losses from natural beach areas are somewhat lower because of surface cover and moisture variations discussed in chapter eight.

6.2 Independent Variables and Correlations

The simultaneous measurement of a large number of microclimate variables during the test periods permitted a thorough investigation of the conditions governing sand loss. Correlations were assessed by linear regression analysis between overnight sand loss (the dependent variable) and each microclimate parameter in turn as the independent variable. Sand losses were also plotted against the independent variables to visually assess whether a non-linear relationship was present. Twenty-three independent variables were assessed with respect to sand losses, including average and maximum wind speeds, air temperature, relative humidity, ground temperature and soil heat flux. The independent variables are listed in table 6.2 with coefficients of determination (r^2) for test block A5 obtained in regression analysis. Each r^2 indicates the proportion of observed variation in test-block sand losses which can be attributed to an approximate linear relationship between sand loss and the independent variable (Devore 1987). Correlation between the sand losses and the independent variable is weak when $0 \leq r^2 \leq 0.25$, moderate when $0.25 < r^2 < 0.64$ and strong when $0.64 \leq r^2 \leq 1.0$ (Devore 1987). Shading in table 6.2 highlights the variables used in further analysis.

independent variables	r-squared
wind speed	
0.5 m avg (tower)	0.41
0.5 m max (tower)	0.27
1.0 m avg (tower)	0.40
1.0 m max (tower)	0.26
2.0 m avg (tower)	0.41
2.0 m max (tower)	0.27
4.0 m avg (tower)	0.42
4.0 m max (tower)	0.28
6.0 m avg (tower)	0.44
6.0 m max (tower)	0.30
friction velocity	0.38
1.0 m avg (site)	0.46
1.0 m max (site)	0.29
air temperature	
3.5 m avg (tower)	0.23
0.25 m avg (site)	0.26
ground temperature	
bottom avg (block)	0.37
middle avg (block)	0.34
0 m avg (site)	0.28
0 m avg (tower)	0.28
3 cm avg (tower)	0.34
soil heat flux	
0 to 3 cm (tower)	0.00
0 to 50 cm (tower)	0.10
relative humidity	
3.5 m avg (tower)	0.00

Table 6.2 Independent variables and r^2's for test-block A5

6.2.1 Wind Speed

Regression analysis indicates moderate linear relationships between the various measures of wind speed and frozen-block weight losses. The highest r^2 of 0.46 for test block A5 was produced by average wind speeds measured at a height of 1 metre at the experiment site. The data show that block weight losses increase linearly as wind speeds increase (figure 6.6). Data from average wind speeds measured at various heights at the tower site show similar patterns with lower values for r^2. Twelve-hour averages are better predictors of sand loss than maximum wind speeds, as shown by the differences in r^2.

Earlier experiments had produced a much stronger relationship between wind and sand loss. All of the coefficients of determination for wind speed in this study are lower than the r^2's of 0.59 to 0.64 found in a 1993 experiment (van Dijk 1993). The 1993 experiment had a different method in which test blocks were suspended in the air at

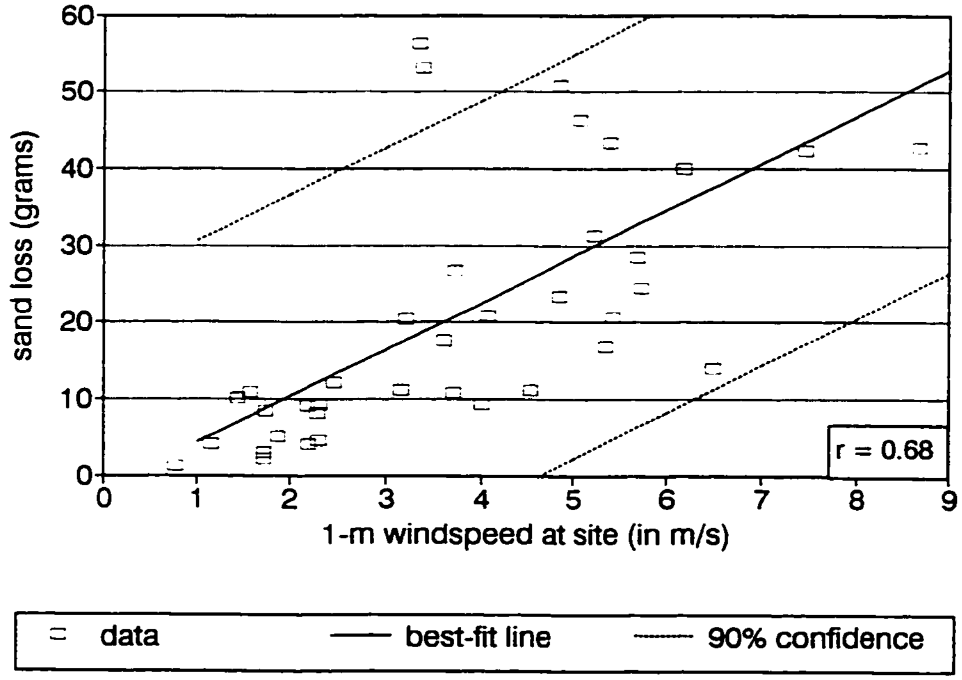


Figure 6.6 Wind speed and test-block weight losses

approximately 1.6 metres above the ground. Lower correlations between wind speed and block losses found by the present study probably reflect the escalated influence of frozen ground properties when the test blocks are located in the ground.

A lower r^2 was produced by friction velocity than by the wind speed averages at the various heights. Friction velocity (u_*) is calculated as the slope of the wind speeds plotted against the logarithms of their heights and has traditionally been used in studies of aeolian processes. Recent research has emphasized the dubious nature of u_* calculations under field conditions where atmospheric stability and instability, changes in surface roughness, turbulence, and measurement or calculation errors produce unrealistic results (Livingstone and Warren 1996, 11; Bauer, Sherman and Wolcott 1992). Use of u_* is based on an assumption that a characteristic boundary layer has developed. The log-linear model may be inappropriate for beaches which are likely comprised of several transitional zones of topography and surface cover (Bauer *et al.* 1996). Values for friction velocity are typically greater at each introduction of surface roughness (Bauer 1991). In winter, the Presqu'ile beach has definite variation in surface cover and roughness (figure 6.7), including notable differences between the experiment site and the weather tower. Nordstrom *et al.* (1996, 669) faced similar problems with non-uniform flow fields in the lee of dunes and concluded that the near-surface mean wind speed was a better indicator of transport potential.

Wind influences sand loss from frozen surfaces through its dual role as a transport agent for water vapour and loose sediment. The movement of wind over a frozen surface stimulates pore-ice sublimation by removing water vapour from the neighbouring atmosphere. By this action, the wind heightens the moisture gradient between the surface and the adjacent air and encourages more water vapour to leave the pore ice. Wind action further stimulates sublimation by removing grains from the surface as they are sufficiently loosened from the pore-ice cementation. As the grains are taken away, they expose underlying frozen sand to increased sublimation. Without wind transport, a

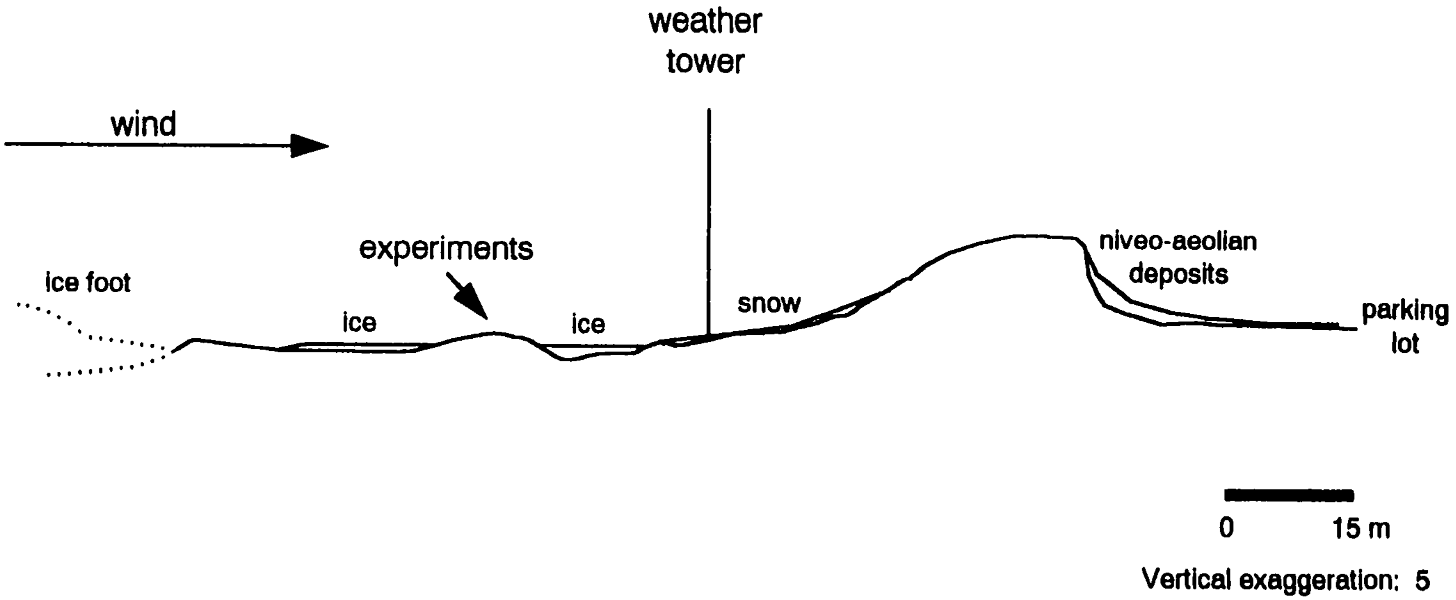


Figure 6.7 Variation in topography and surface cover over the Presqu'ile Beach in winter

desiccated layer builds up, restricting air flow to the sublimation front and slowing down the rate of sublimation.

6.2.2 Temperature

Temperature measurements used in the regression analysis included air and ground temperatures from the tower and experiment sites and the soil heat flux calculated from ground temperature measurements near the tower. Temperatures from aspirated thermocouples located near the tower were not included in the analysis because of significant differences in surface cover between the measurement and experiment sites during much of the study (refer to figure 6.7). Soil heat flux was calculated from temperatures at two depths and the equation

$$Q_G = -k_s \frac{(\overline{T}_2 - \overline{T}_1)}{(z_2 - z_1)} \tag{6.1}$$

where $\overline{T}$ is mean soil temperature at depth z, the numbered subscripts refer to levels in the soil, and k_s is the thermal conductivity assumed to be 2.2 W m^{-1} K^{-1} for frozen sandy soil (Oke 1987, 43-4). Soil heat flux results given in table 6.2 and discussed below are denoted by measurement depths.

There is a borderline weak/moderate relationship between air temperature and sand loss. The highest r^2 of 0.26 was produced by the thermocouple measurement of air temperature at a height of 0.25 metres near the experiment site. Scatter plots show a wider range of sand losses at warmer temperatures, but there is no evidence for any non-linear relationship.

Regression shows stronger relationships between ground temperature and sand loss. Values of 0.27 to 0.37 for r^2 indicated moderate linear relationships with sand loss; the highest r^2 of 0.37 came from measurements of block temperatures at the bottom of the test tray (figure 6.8). These correlations are much stronger than r-squareds of 0.18 to 0.23 measured in the 1993 experiments (van Dijk 1993) and are also significantly higher

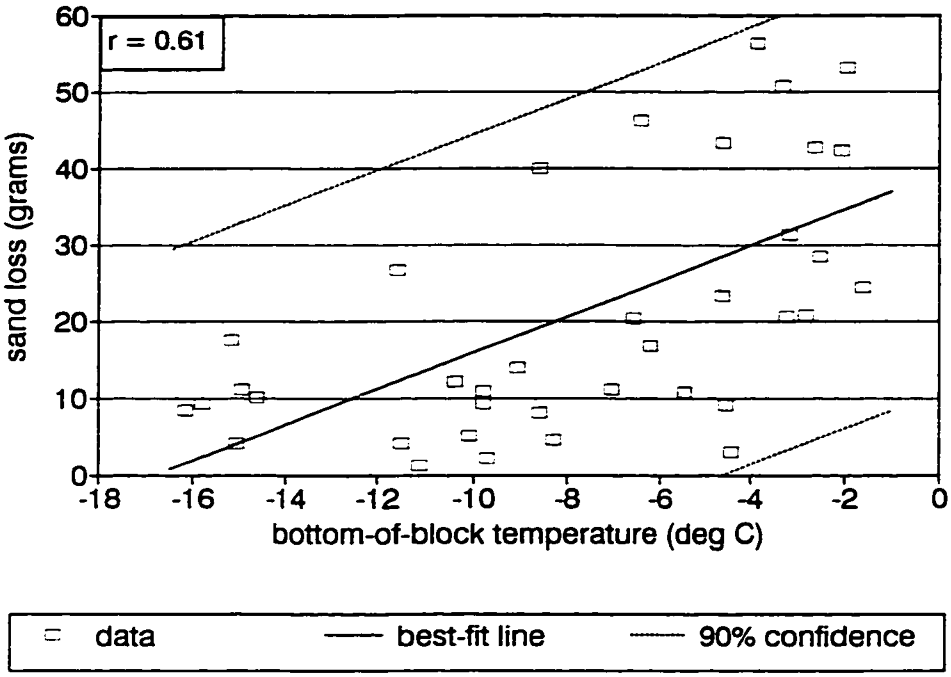


Figure 6.8 Test-block weight loss and temperature at block bottom

than the calculated values for r^2 for air temperatures. Changes to method which allowed the test blocks to approximate natural surfaces made the improved correlations possible. In the earlier experiments, suspended test blocks quickly adjusted to ambient conditions, and block and air temperatures were comparable. In the 1996-1997 experiments, block temperatures were more likely to approximate frozen beach temperatures than air temperatures, and higher coefficients of determination reflect the importance of surface over air measurements.

Soil heat flux is only weakly correlated to block weight losses. The weak correlation can be attributed to surface differences between the ground-temperature measurement site and the experiment location. The most noticeable difference was frequent snow and ice cover at the ground-temperature site, both of which affect the transfer of heat between the ground and atmosphere. It is not surprising, then, that the soil heat flux measured in the top centimetres of the ground near the tower bears little relation to the processes occurring in the top centimetres of the experiment site. As the soil heat flux is averaged over a larger depth of approximately 0.5 metres, the surface effects are offset by the more stable temperatures at depth. The results are weak correlations with experiment results showing that there are some similarities in temperature regimes.

The amount of sand released by pore-ice sublimation generally increases with warmer temperatures. Temperature changes the bond energy of the ice surface and governs both the energy necessary to overcome molecular bonds and the heat energy available for sublimation. Measures of ground temperature are better indicators of ice strength and changes of state than air temperatures. These results attest to the importance of frozen surface characteristics in sand release. Correlation remains lower than correlations between wind speed and sand losses. It appears that a powerful wind can offset low temperatures, whereas calm to low wind conditions at warm temperatures inhibit pore-ice sublimation.

6.2.3 Relative Humidity

The regression analysis revealed almost no correlation between relative humidity and test-block sand loss, an outcome which is substantially lower than the literature would suggest. An r^2 of 0.004 is quite a bit smaller than the 0.16 reached in the 1993 tests, and does not support the influential nature of relative humidity suggested by other researchers. Graphing the data shows consistent scatter over the measurement range with no apparent non-linear relationships (figure 6.9). Aguirre-Puente and Sukhwal (1984) claim that there is no significant change in sublimation rate when the relative humidity is greater than 80%, but very few high humidities were recorded during the experiments. The only explanation to be offered at this time is that the effects of wind and block temperature considerably outweighed and masked any effects of relative humidity.

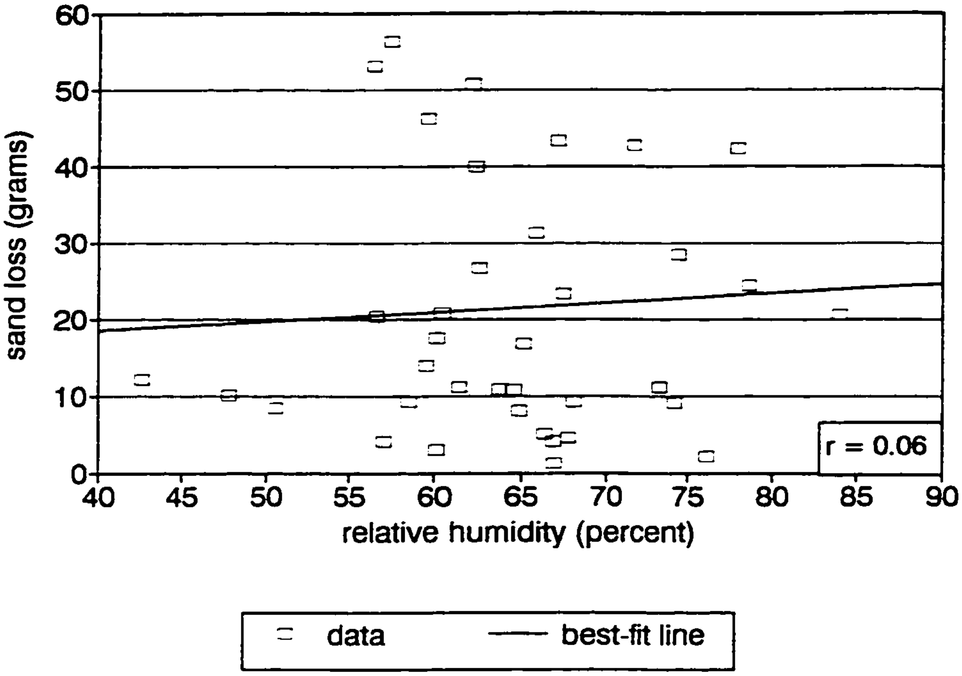


Figure 6.9 Relative humidity and test-block weight loss

6.2.4 Block Position[1]

Analysis revealed distinct trends in correlation between block weight losses and each of the independent variables with block position. Consistently higher values for r^2 were recorded for blocks on the windward side of each tray, i.e., blocks A1, A3, A5, B1, B3, and B5 (refer to figure 6.5 for block positions). The highest values for r^2 for each tray were produced by blocks A5 and B1, which occupied the northwest corners of their respective trays.

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[1] Earlier it was revealed that block positions for 7 nights were corrected in analysis to remove changes in wind direction from affecting further analysis. The correction holds true in this discussion and is not mentioned unless it uniquely affects the discussion. To be completely accurate, each description of a block position should have a qualifying statement, such as "block A1 (A2 when the wind was from the east)...". These statements are omitted for ease of discussion.

25 Feb '97
winddir=
246 deg

A6 23.56	A4 21.72	A2 27.35
A5 42.78	A3 38.03	A1 52.45

B2 27.71	B4 14.91	B6 16.8
B1 67.86	B3 27.7	B5 23.54

3 Mar '97
winddir=
62 deg

A6 53.14	A4 52.6	A2 58.72
A5 44.82	A3 46.72	A1 44.84

B2 63.64	B4 43.49	B6 37.14
B1 55.26	B3 37.22	B5 34.2

Figure 6.10 Block weight losses (in grams by position) for two experiment nights

A comparison of block weight losses (rather than derived r^2) shows larger losses from blocks in the windward row of the tray (illustrated in figure 6.10). On tray A, block A5 once again recorded the highest values. Losses from block B1 cannot be compared to losses from other blocks on tray B because of differences in water contents.

The differences in values for r^2 and weight losses suggest that they are influenced by block position with respect to wind direction. Blocks A5 and B1 occupy the most windward position on their respective trays. Whereas every effort was made to approximate natural conditions, there were unmistakeable differences and discontinuities between the surrounding frozen beach and the test blocks. The largest of these differences was water content which affected surface erodibility. Frozen test blocks were more erodible at water contents of 6-10% than the surrounding saturated and oversaturated frozen material. It is possible that, as wind encountered the more erodible test-block surfaces, some of the wind's momentum was absorbed by the initial block, thereby reducing the downwind influence.

Another possible explanation is that material removed from the windward block prevents erosion from downwind blocks. There was no evidence of loose particles on any blocks at the end of most test periods. A converse hypothesis that material from windward blocks abrades downwind surfaces and increases erosion is discounted by decreased downwind losses.

Experiment results suggest that either the upwind test blocks are more erodible than their downwind counterparts or the downwind test-blocks are sheltered from erosion in some way. Evidence was not available to determine which was the case. Upwind results are used in the discussions of this chapter because they exhibited stronger correlations, but all data were analysed to confirm the results.

6.3 Sand Supply Equations

Multiple regression analysis, using the influential independent variables from the linear regression, was employed to derive an equation for frozen surface sand loss. The chosen independent variables were average 1-metre wind speed at the site and block temperatures measured at the bottom of the trays. The multiple regression analysis was applied to each test-block position in turn, and values for r^2 ranged from 0.36 (block B4) to 0.64 (block B1). The following equation describes the relationship between frozen surface sand loss, wind speed and ground temperature for block B1 (r^2 = 0.64):

$$L_6 = 7.3v + 1.6t + 13.9 \qquad (6.2)$$

where L_w is the 12-hour sand loss (in grams) of a frozen test-block with water content w, v is the 12-hour average wind speed at 1 m height (in m/s), and t is the 12-hour average temperature measured at the bottom of the blocks (in °C). Standard deviation for L_6 is 15 grams. The equation shows that as wind speed and temperature increase, frozen surface sand loss increases.

Coefficients of determination for the multiple regression equations were low compared to values of 0.92 to 0.94 in the 1993 experiments. Reasons for the drop in correlation may be those discussed with respect to individual wind speed and temperature results: the increasing influence of surface properties relative to wind characteristics on the sublimation and sand-loss process. Furthermore, the experiment blocks were exposed to more complex influences as they approximated the natural beach surface. A corresponding increase in measured variation may reflect the influence and interactions of variables not yet identified.

The data were further tested by multiple regression analysis including relative humidity as an independent variable. The rationale for this decision was that any influence of relative humidity may have been masked during simple regression by the effects of temperature and wind speed. A significant improvement in correlation resulted from including relative humidity with wind speed and temperature in multiple regression analysis. Coefficients of determination now ranged from 0.51 to 0.70, establishing the equations firmly on the lower border of a strong relationship. The equation for block B1 (r^2 = 0.70) which includes the three independent variables is

$$L_6=7.8v+2.3t-0.60h+54.9 \tag{6.3}$$

where h is the 12-hour average relative humidity (%). The standard deviation for L_6 is 14 grams. The negative coefficient for relative humidity indicates that increasing humidity decreases sand loss.

6.4 The Moisture Factor

The influence of water content on frozen surface sand loss was determined by a separate set of field experiments described in chapter four. Test blocks with water contents ranging from 2% to 22% were exposed to field conditions on 15 nights. Two nights of data were taken out of the analysis because rain and above-zero temperatures caused some of the blocks to melt and fall. On an additional two nights, air temperatures stayed above zero for several hours without causing any blocks to fall, and snow occurred on two other nights. Data from the four borderline nights were used (with caution) because the experiments measured changes between blocks which were exposed to identical conditions. A large range of microclimate conditions were recorded during the 13 experiment nights, with 12-hour averages ranging from -1.5°C to -16.9°C for temperature, 55% to 83% for relative humidity, and 1 m/s to 5.1 m/s for wind speed. Block sand losses ranged from a low 4.74 g for a test block with 20.8% water on 2 February 1997 to a high 598.63 g for a test block with 3.0% water on 5 February 1997.

The search for a water content-sand loss relationship began with plotting the data; a sample of six nights are graphed in figure 6.11. From the graph, it is evident that sand losses have an inverse relationship to block water content. None of the experimental results contradicted this conclusion; if block A had a higher water content than block B, block A *always* lost less sand than block B. In figure 6.11, the relationship between sand loss and water content appears to be exponential instead of linear.

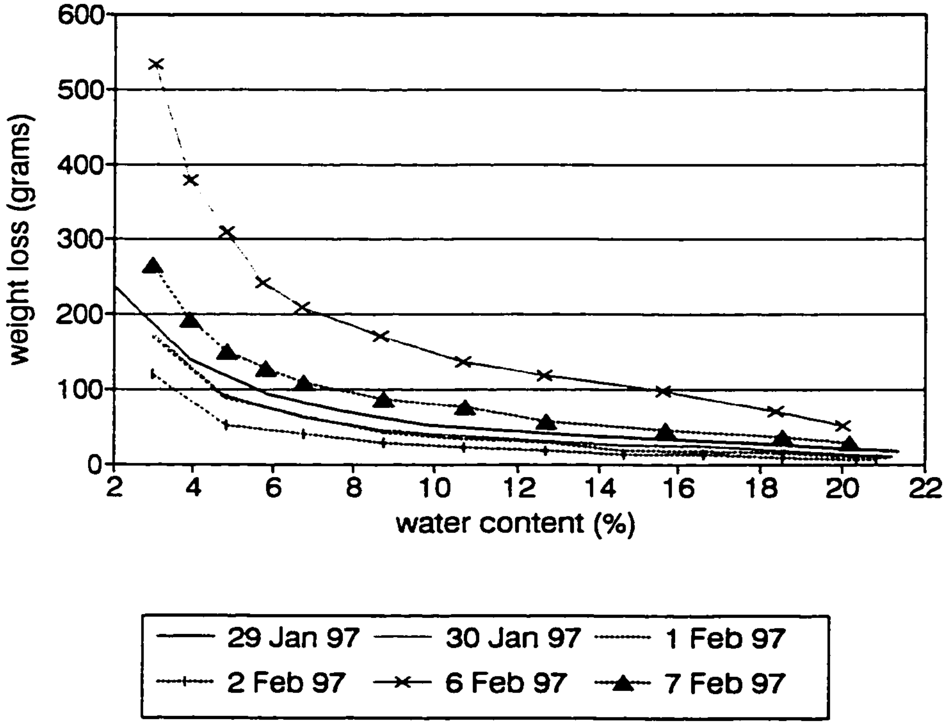


Figure 6.11 Test-block sand losses by water content on selected experiment nights

function	transformation	linear form
exponential $y = \alpha e^{\beta x}$	$y' = \ln(y)$	$y' = \ln(\alpha) + \beta x$
power function $y = \alpha x^{\beta}$	$y' = \ln(y)$, $x' = \ln(x)$	$y' = \ln(\alpha) + \beta x'$

Table 6.3 Intrinsically linear functions and their transformations (after Devore 1987)

Exponential and power-law relationships were investigated through logarithmic (base *e*) transformations of sand loss, water content, or both. The transformations were intended to produce a linear function which could then be defined by regression analysis (table 6.3). Values of r^2 of 0.88 to 0.96 indicated that the relationship between water content and sand loss was best described by a power function, such as

$$L=1052w^{-1.56} \tag{6.4}$$

derived from 1 February 1997 with a standard deviation of 1.18 grams for *L*. The water-content experiments produced fourteen such power functions for sand loss, each having different α and β coefficients reflecting the different experiment conditions. The power function relationship is consistent with unconfined compression test results which demonstrated that frozen-sand cohesion varies as a power function of water content.

Foley (1997) examined the same data-set with respect to producing an equation relating water content, sand loss, and local conditions. Averaging the α and β coefficients produces a line which is very similar to regression analysis of all the data together (Foley 1997, 29). Correlation is weaker ($r^2 = 0.42$) and the equation cannot account for 'extreme' events, such as high-wind warm-temperature conditions when sand losses are heightened (Foley 1997). Further analysis using coefficients from the 1993 experiments produced an equation which included water content, wind speed, temperature and relative humidity, but consistently overpredicted sand loss (Foley 1997).

In the current study, the interaction between water content and local conditions in the process of surface sand loss were investigated directly from experimental results. Tray B contained test-blocks with water contents of 6%, 8%, and 10%. Y-intercepts and coefficients for wind speed, temperature, and relative humidity were examined in the light of water content influences. Each regression analysis produced a strong power-law relationship between water content and the dependent variable. This result is important: it indicates that the interaction between water content and sand loss is reflected in the interactions between water content and each of the local variables. The power-law relationship holds true for the separate parts of the defining equation, instead of a linear relationship between water content and temperature or an exponential relationship between relative humidity and water content, for example.

The results permit a single sand-loss equation which includes water content, wind speed, temperature and relative humidity:

$$\begin{aligned} L_w = (0.052w^{-1.74})\,v + (0.43w^{-0.58})\,t \\ - (0.15w^{-0.59})\,h + 17.1w^{-0.48} \end{aligned} \tag{6.5}$$

where water content w is expressed as a decimal. When 0.06 is substituted for w:

$$L_{0.06} = 6.95v + 2.20t - 0.79h + 66.0 \tag{6.6}$$

equation 6.5 becomes very similar to equation 6.2. The moisture experiments demonstrated that the power functions hold true from 2% to 22% water content. Equation 6.5 can be used to predict sand loss for a range of water contents.

Equation 6.5 and the best-fit equations from the multiple regression analysis were compared to each other and to measured sand losses as a check of their applicability. Sand losses were calculated from equation 6.5 and equations like 6.2 for the wind speeds, temperatures and relative humidity measured on the experiment nights. Differences between the two methods of prediction and measured sand losses were compared. Both equations fit the data well and produced similar standard deviations of approximately 12 grams. Of the two methods of prediction, equation 6.5 is the most useful because it is not limited to a specific water content.

6.5 Extending Experiment Results to Larger Areas

Relatively small test areas were exposed to erosive conditions in the 1996-1997 experiments, but the results can be applied to larger areas. Test-block surfaces had dimensions of 9.5 cm x 9.5 cm, or 9 x 10^{-3} m^2. One gram of sand released from a test block corresponds to 111 grams released from a square metre of beach under the same conditions. A conversion factor can be added to equation 6.5 to form the following equation:

$$\begin{aligned} L_w = [& (0.052 w^{-1.74}) v + (0.43 w^{-0.58}) t \\ & - (0.15 w^{-0.53}) h + 17.1 w^{-0.48}] \cdot 111 \end{aligned} \tag{6.7}$$

where L_w now gives the sand loss in g m^{-2}.

The areal extent of exposed frozen sand in a beach/dune complex will determine the total amount of sand which is released from the frozen surface by pore-ice sublimation and can be moved by wind. In many cases, the total area of frozen exposed sand will be less than the total surface area of a beach/dune complex. For example, in 1997 the Presqu'ile beach could be divided into six characteristic zones (table 6.4). Over the winter, rain and melt-water which could not seep through the frozen sand would collect in two low-lying areas of the beach and freeze as temperatures dropped. For most of the winter these areas (zones 3 and 5) were covered with ice which protected the underlying sand from wind erosion. Surface protection was also evident in zone 6 which served as a deposition area for blowing and drifting snow. Wind erosion in the study area was mostly limited to zones 1, 2, and 4 with a total area of approximately 1920 m^2 or 46% of the beach. Day-

	approximate zone width	description	approximate area
zone 1	4 m	sloping upward from ice-foot to berm crest	240 m^2
zone 2	12 m	gently sloping downward from berm crest	720 m^2
zone 3	24 m	low-lying area, often ice-covered	1440 m^2
zone 4	16 m	higher midbeach area with winter pebble lag	960 m^2
zone 5	36 m	low-lying area, often ice-covered	2160 m^2
zone 6	9 m	sloping upward to foredune, often snow-covered	540 m^2

Table 6.4 Characteristic zones of Presqu'ile Beach study area in winter

to-day boundaries and areas of exposed frozen sand depend on weather, melting, and blowing snow patterns.

A twelve-hour period from the 1997 winter can be chosen as an example of how sand movement on the Presqu'ile Beach can be predicted using the information of this chapter. The chosen time-period is from noon to midnight on 25 February. Snow had fallen in the late morning of the same day, but increasing winds had cleared most of zones 1 and 2, exposing a 14 m x 60 m area of frozen sand by noon. Field measurements that day indicated water contents of 22% and above for the area. During the 12-hour period, average wind speed at 1 m was 7.8 m/s, ground temperature was -2.9°C, and relative humidity was 71%. Substituting these numbers into equation 6.7 produces

$$L_{.22} = [(0.052 \cdot 0.22^{-1.74})7.8 + (0.43 \cdot 0.22^{-0.58})(-2.9) - (0.15 \cdot 0.22^{-0.59})71 + 17.10.22^{-0.48}] \cdot 111 \tag{6.8}$$

which equals 1332 gm^{-2}. This translates into approximately 112 kg of sand eroded from the 840 m^2 area in the twelve-hour period. Winds during that period were consistently around 7-10 m/s and all of the sand which was released from the frozen surface moved across the beach to the dunes. Sand movement was confirmed by observations in the afternoon and evening.

6.6 Summary

Sand supply is governed by microclimate and surface variables on frozen sands with greater than 1% water content. Experiments have shown that wind speed, relative humidity, and frozen sand temperature and water content control the amount of sand which is released from the frozen surface by pore-ice sublimation. Optimum conditions for sand release involve high wind speeds, low relative humidity, warm temperatures and low water content of the frozen sand. With a set of fairly simple measurements--wind speed at 1-metre height, relative humidity, ground temperature at 0.04-metre depth, and surface water content--the amount of sand released from specified areas of frozen sand is predicted in equation 6.7.

The amount of sand released from any frozen surface where water contents exceed 1% is the amount of sand that is available for aeolian transport. It follows that equations which define sand release in terms of local conditions also define the amounts of sand which can be entrained and moved by the wind. Thus, amounts calculated with equation 6.7 are predictions of potential aeolian transport from specified areas. Sufficiently strong winds remain a prerequisite for movement. In the absence of strong winds, sand which is released from the frozen surface stays in place and a layer of dry sand forms on top of the cemented frozen sand. Pore-ice sublimation continues at depth, albeit at decreasing rates, and the amount of sand available for movement gradually increases over time.

In an active winter beach environment, such as Presqu'ile, strong winds are frequent and released sand does not remain long on the surface. There were few observations of dry sand on the top of the test blocks during the experiments. Layers of desiccated sand which do form during periods of beach inaction are quickly removed when winds increase above thresholds for movement. The amount of transported sand is the amount of sand that has been released from the frozen surface during the period of aeolian inaction.

Chapter Seven

THE COLD-AEOLIAN MODEL

Blow, blow, thou winter wind!
Shakespeare

The cold-aeolian model combines surface limitations with sand supply mechanisms to describe and predict aeolian activity in cold environments. The defining conditions, or model inputs, are 1) water content of exposed sand or surface moisture in the form of ice and snow, 2) wind speed measured at a height of 1 metre, 3) temperature measured 3-4 centimetres below the frozen surface, and 4) relative humidity. Three broad types of cold-aeolian activity are possible under sub-zero temperatures: a protective layer between the frozen sand and the atmosphere can prevent surface erosion, a layer of uncemented sand can increase in depth as pore-ice sublimation occurs without sand transport, and wind can effect the erosion, transport and deposition of sand. Various combinations of local conditions are used to predict cold-aeolian activity and vice versa. Conditions can also be used to assess the potential for movement from designated areas.

7.1 Model Inputs: Local Conditions

Cold-aeolian activity can be defined and predicted based on local variables. Specific combinations of surface moisture, wind speed, temperature and relative humidity determine whether aeolian or related activities are occurring. Sand movement is quantified by providing the local data for equation 6.7. The variables have well-defined roles and formats in the cold-aeolian model; these are described below and depicted in a flow chart later in this chapter (pages 158-168). The resolution for model inputs and predictions is 12-hour periods.

7.1.1 Surface Moisture

In cold-aeolian environments, surface moisture is found in three different forms, each of which has a specific effect on aeolian processes. Snow and ice on the ground surface prevent aeolian transport of sand altogether, while pore ice (measured as the water content of exposed sand) limits the supply of sand to aeolian processes.

7.1.1.1 Snow and Ice

A layer of snow or ice on top of frozen sand prevents all sediment transport by wind. The wind energy is restricted to the surface of the snow or ice and cannot act on the underlying frozen sediments. Surface protection is not dependent on the characteristics of the snow and ice, or even on the thickness of the sheltering layer. The underlying frozen sand is protected by the mere existence of a layer that separates it from wind action.

The characteristics and thickness of the protective layer do govern the potential of frozen sediments to move in the future. Thin or porous layers are more quickly removed by melting and evaporation. The physical removal of surface protection by wind is limited to snow which retains its distinct particles. Fresh snow, especially when it is cold and relatively dry, is prone to drifting and blowing by wind. Older snow, which has become aggregated, and ice are forcibly removed by wind only under exceptional circumstances. The dense frozen moisture disappears under sublimation-drying or melting and evaporation. Sediment transport does not resume until the protective layer is gone.

The cold-aeolian model accepts only a simple yes/no answer to the question of whether ice is present. The model accounts for ice disappearance by repeating the question at the beginning of each time period.

The model also asks for a yes/no answer with respect to the presence of snow. A positive response prompts a request for two additional pieces of information: the type of snow and the wind speed at a height of 1 metre. These data enable the model to assess whether snow is moving. Different types of snow have characteristic wind thresholds for movement (table 7.1). The twelve-hour time periods of the model do not permit the same level of detail as the snow surface conditions of table 7.1. Instead, snow condition is divided into two broad categories: (1) 'fresh' cold snow in which individual particles

snow surface conditions	u_{*t} (m/s)	V_t (m/s at 1-metre)
loose fresh dry snow at $<-2.5^{\circ}$C	0.15	4.0
newly fallen snow at 0°C	0.25	5.5
slightly aged (several hours) snow near 0°C	0.40	8.5

Table 7.1 Types of snow and thresholds for movement (after Kind 1990, 857)

remain distinct and are easily moved and (2) 'aged' or warmer snow in which particles have undergone some metamorphosis and aggregation. A threshold wind speed of 4 m/s is assigned to the first category whereas no movement is assumed for the latter. The snow categories require qualitative assessment on the part of the observer.

7.1.1.2 Water Content of Exposed Frozen Sand

Frozen sand exposed to wind has different reactions based on surface water content. Three responses are possible:

1) Aeolian entrainment of sediment is not affected by water content. Grain size and wind speed control entrainment and transport rates. Aeolian activity of this sort occurs on frozen sediments with negligible water content and no cementation.

2) Aeolian entrainment varies with water content. Higher thresholds for movement, which are water-content dependent, determine rates of entrainment and transport.

3) Direct entrainment is not possible from frozen sediments when the water content exceeds a certain level. The weak- to very strong-cementation produced over a wide range of water contents restricts sediment movement to the individual grains which are released from the frozen surface by pore-ice sublimation.

By far the majority of surface water contents produce frozen sediments whose response to wind fall into the latter category.

The cold-aeolian model requires measurements of surface water content by mass. Water content is indicated as a percentage (e.g. 15%) which is converted to a decimal (e.g. 0.15) by the model when required for calculations. Measurements of water content should be taken from the top few centimetres of the frozen sand.

7.1.2 Wind Speed

The influence of wind speed on cold-aeolian activity depends on the condition of the frozen surface. Over snow- and ice- covered surfaces, wind enhances sublimation-drying or physically removes snow from the area. A strong wind can directly entrain sediment and maintain saltation on a frozen exposed surface with negligible cementation. Increasingly stronger winds are needed to directly remove sand from frozen sand when pore-ice cohesion becomes noticeable. Above a critical wind speed, the wind is an erosive agent which removes surface particles and transports them downwind. Below the critical wind speed, the wind plays a vital role in the sublimation of the remaining pore ice. Direct entrainment is not possible from most frozen sands because the surface grains are too strongly bound by pore ice. As a result, the wind's role is limited to transporting water vapour away from the sublimation area and removing individual grains as they are released from the surface.

One metre is the designated measurement height for wind speed in the cold-aeolian model. The metre height fulfils the requirements of the sediment supply equation (6.7) developed in chapter 6. A threshold wind speed for Presqu'ile Beach sand is calculated for this measurement. A sediment flux equation using the 1-metre wind speed already exists (Dackombe and Gardiner 1983), but a conversion factor is needed to produce units corresponding to equation 6.7.

7.1.2.1 Threshold Wind Speed

The threshold shear velocity for Presqu'ile Beach sediments was calculated from Bagnold's equation and then converted to an equivalent 1-metre wind speed. Bagnold's (1941) equation for threshold shear velocity states that

$$u_{*t} = A\sqrt{\frac{\sigma-\rho}{\rho} g d} \qquad (7.1)$$

where A is a constant which equals 0.1. A threshold shear velocity of 20.1 cm/s was calculated for Presqu'ile Beach sand where d = 0.21 mm (Menhennet 1994), σ = 2.65 g/cm^3 (Nickling 1994) and ρ = 1.35 kg/m^3 between 0 and -20°C (Monteith 1978). The threshold shear velocity is converted to an approximate wind speed of 6 m/s at a metre height using the logarithmic wind profile equation

$$u_z = \frac{u_*}{k} \ln \frac{z}{z_0} \qquad (7.2)$$

where k = 0.41 and $z_0 \approx d/30$.

7.1.2.2 Sand Transport on Uncemented Presqu'ile Sand

Calculation of the sediment flux on uncemented Presqu'ile sand is based on the following equation

$$q = 1.5x10^{-9}(V-V_t)^3 \qquad (7.3)$$

where both wind speed (V) and threshold wind speed (V_t) are measured at a height of 1 metre (Dackombe and Gardiner 1983, 174). Equation 7.3 was derived from Bagnold's (1941) sediment flux equation for average dune sand (d = 0.25 mm) which was naturally graded. The sediment flux of equation 7.3 has units of tonnes (m-width)$^{-1}$ hour^{-1}.

A conversion factor is needed to compare the sediment flux on uncemented sand to sediment supply from cemented sand, L, which has units of kg m^{-2} (12-hour)$^{-1}$. Values for q represent the mass of sediment passing through a plane perpendicular to the wind of unit width of infinite height above the ground per unit time. The surface area supplying the moving sand which passes the plane corresponds to saltation lengths which are about 12 to 15 times the height of bounce (Livingstone and Warren 1996, 16). Most saltating grains travel within 30 cm of the bed (Horikawa and Shen 1960), and a saltation height of 30 cm would correspond to an average jump length of 4.5 metres. Assuming that the mass of sediment in q represents a normal distribution of saltation jumps, the source area for q has a length of 4.5 metres. This estimate is very close to the observation that 97% of total blown sand from upwind will fall within four metres of the waterline if a pond is located downwind (Horikawa 1988, 479-480). With the upwind length of 4.5 m, equation 7.3 becomes

$$Q = 4x10^{-6}(V-V_t)^3 \tag{7.4}$$

which is in kg m^{-2} $(12\text{-hour})^{-1}$.

7.1.3 Temperature

Temperature provides the criteria by which cold-aeolian activity is defined; temperature also influences the strength of ice bonds after they have been created. The important upper limit for cold-aeolian activity is the freezing temperature of 0°C. Aeolian activity is governed by a different set of equations and relationships above the freezing point. Below 0°C, temperature influences the bond strength and the rate at which grains are released from the frozen surface.

The cold-aeolian model requires air and ground temperatures. Air temperature is chosen, for practical purposes, to determine whether the processes are cold-aeolian. Temperatures measured directly at the air/ground interface can also be used, but few of these data were gathered in Presqu'ile field tests. The model uses below surface temperatures to determine grain release by sublimation. The 3-4 centimetre measurement depth is the closest to the depth used in the experiment results of chapter six.

7.1.4 Relative Humidity

Relative humidity is the fourth variable used in calculations of sediment supply from frozen sands. Greater saturation of the air near frozen sand inhibits the drying of the surface by pore-ice sublimation. The model uses a general measure of relative humidity taken from a probe located several metres above the frozen surface.

7.2 Model Results: Cold-Aeolian Activity

Three broad types of beach activity are possible under sub-zero temperatures. The frozen ground can be sheltered from wind erosion by a protective layer, exposed sand can be released from the frozen surface without transport occurring, and exposed sand can be released, entrained by wind, and transported across the frozen surface. The cold-aeolian model indicates which activity occurs on the frozen surface and can predict sand release and transport where appropriate.

7.2.1 Surface Protection

Cold-aeolian movement of sediment can be halted completely by a surface cover of snow or ice. Wind cannot act upon the frozen sand and its energy is absorbed by the protective layer. Sediment movement does not resume until the surface cover is removed by melting, sublimation-drying, or the aeolian movement of snow.

Surface protection by snow and ice can have residual effects after the snow and ice has disappeared. Moisture transfer between the saturated snow/ice layer and less-saturated frozen sand can leave the frozen soil with higher water contents after the snow or ice is gone. Sediment saturation is likely to occur when water remains above impermeable frozen ground during warm periods and freezes as temperatures drop. Water can also be transferred from the base of snow-packs to underlying sand if there is a moisture gradient from one to the other.

The cold-aeolian model indicates that sand movement halts when snow and ice cover the surface. Calculations of sand release and transport are suspended until the underlying frozen sand is exposed once more. In addition, it is assumed that any loose sand--accumulated on the surface during calm periods--will gain moisture from the ice or snow and refreeze. When the sand is exposed, surface grains must be released again before they can move.

7.2.2 Sand Release without Transport

Sand release without transport occurs when there is no surface protection but winds are too weak to entrain released sand. Grains are released from the frozen ground as the pore ice, which controls cementation, sublimates. Wind speed, temperature, relative humidity and surface water content determine the rate at which grains are released. The process is described by equation 6.7:

$$L_w = [(0.052w^{-1.74})V + (0.43w^{-0.58})t - (0.15w^{-0.59})h + 17.1w^{-0.48}] \cdot 0.111 \tag{6.7}$$

where L_w is the sand released from the frozen surface in kg m^{-2} $(12\text{-hour})^{-1}$, w is water content by mass (as an integer not a percent), V is the wind speed at a height of 1 metre, t is the ground temperature measured in degrees Celsius 3-4 cm below the surface and h is percent relative humidity. The released particles remain in place as long as wind speeds are too weak to entrain and transport the sand. The surface layer of loose grains increases in depth over time as sublimation-drying moves down into the frozen ground.

The rate of pore-ice sublimation gradually decreases when the process is allowed to continue for a substantial time without wind removing the dried sediment. The dry layer inhibits pore-ice sublimation at depth by dampening thermal and vapour diffusion above the sublimation front. The net result is less sand released over prolonged periods of time when sediment movement is not occurring.

The cold-aeolian model calculates the amount of sand released by pore-ice sublimation when the frozen sand is free from surface cover. The sand released in successive time periods produces a cumulative total for loose dry sand on top of the frozen layer. The model reduces the rate of loose particle production when the thickness of the desiccated layer reaches a centimetre. This is accomplished by multiplying the sand released (L_w) by 1/S where S = 1 for the first centimetre, 2 for the second centimetre, 3 for the third, to a maximum of S = 4 for the fourth centimetre and beyond. Each centimetre depth of released sand corresponds to approximately 14 kg m^{-2} of sand.

7.2.3 Sand Movement

Sand movement takes place when wind speeds are high enough to entrain the sediment. Transport depends on the amount of surface material available for movement which is, in turn, strongly controlled by water content. Water content boundaries enable the cold-aeolian model to distinguish between supply-limited and transport-limited movement.

Dry sediments pose no surface restrictions to aeolian movement. Below 0.5% water content, frozen sands behave as loose dry material. Entrainment occurs when wind exceeds the appropriate threshold velocity for the grain size. The sediment supply for aeolian transport is essentially unlimited.

Very weakly cemented sediments inhibit sand movement but high wind speeds can entrain material despite the pore-ice bonds. Between 0.5% and 1% water content, stronger winds can forcibly overcome some of the ice bonds to push sand grains into motion. The remnants of ice quickly disappear as the mineral particles move through the air. The strong winds necessary to break ice bonds also encourage pore-ice sublimation in the frozen ground. Particle entrainment is a combination of weakly-cemented particles being directly entrained and sand grain release by sublimation.

Firmly cemented sediments can only be entrained by wind after they have been released from the surface. After a period of inaction, the loose sediment layer on the surface will be removed when wind speeds exceed the threshold for movement. With no loose layer, the wind needs ongoing pore-ice sublimation to supply sediment for transport. Therefore, the transport rate is governed by the sublimation rate. Wind speeds which are high enough to entrain sediment also encourage relatively high rates of particle release from the frozen ground. Loosened sand does not build up on the surface and the high sublimation rates are maintained over time.

The cold-aeolian model recognizes transport-limited sand movement when surface water contents are low (figure 7.1). The upper limit for this movement ranges from a water content of 0.5% at a wind speed of 6 m/s up to a water content of 1% when wind speeds exceed 16 m/s. Sand transport is calculated by equation 7.4.

The model recognizes supply-limited transport for a large range of water contents extending from either 0.5% or 1% to saturation (figure 7.1). The most important assumptions made by the model are that aeolian processes are supply-limited under these conditions and therefore equations which predict sediment supply can be used to predict sediment transport. Only sand which has been released from the frozen surface can be transported and when winds exceed the threshold, all released sand is transported. Thus,

$$Q = L_{total} \tag{7.5}$$

where L_{total} is the amount of sand released during the current 12-hour period (L_w) plus the amount of released sand left on the surface from previous time periods. Downwind abrasion is ignored by the model.

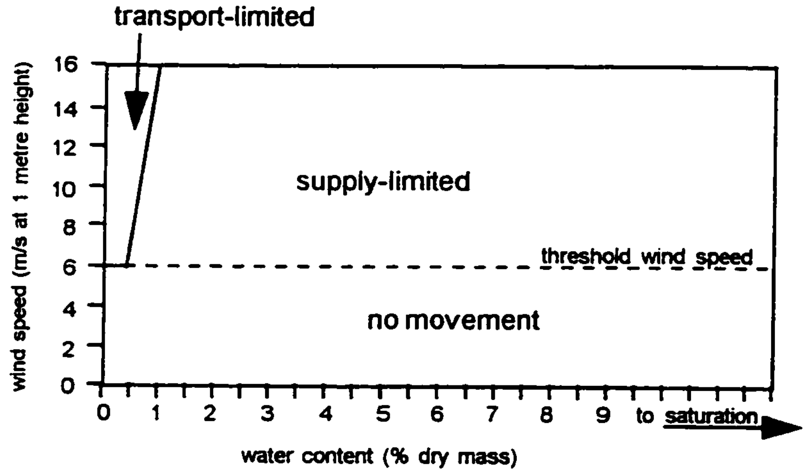


Figure 7.1 Water content boundaries for transport- and supply- limited sand movement

7.3 Condition-Process Interactions

There are many possible mixtures of local variables, but each combination produces a specific outcome. This makes prediction possible. Given a defined set of local conditions, a particular cold-aeolian activity is expected. The opposite is also true: if a cold-aeolian phenomenon is observed, specific conditions are expected.

Figure 7.2 illustrates the cold-aeolian processes which are active under specific water content and wind conditions. A constant sub-zero temperature and a grain diameter of 0.21 mm are assumed. Wind speed determines whether or not available sand is moving, and a threshold wind speed of 6 m/s marks the division between aeolian entrainment and no movement. The condition of the frozen surface--quantified by surface water content--determines how much sand is moving. Loose sand (0-0.5% moisture; boxes A and B) offers an unlimited supply of sediment to aeolian processes, and very weakly cemented frozen sand (0.5-1% moisture) does the same under sufficiently strong winds (bottom of box B). A limited supply of sediment is available on very weakly cemented frozen sand under weaker winds (C and D) and more firmly cemented sand under all wind speeds (above 1% water content; E and F). Pore-ice sublimation is the dominant activity, and entrainment of the released grains occurs when the wind speed exceeds the threshold for loose sand. There is no sediment available for movement when snow and ice cover the frozen sand (G, H, I, J). Activity is restricted to sublimation-drying of the snow and ice surface, and aeolian deflation of fresh snow when winds exceed the 4 m/s threshold.

Two important variables--temperature and relative humidity--were held constant in figure 7.2 for ease of illustration. Both of these variables influence the rate of particle release by pore-ice sublimation. However, neither of these variables change the boundaries between the various types of activity outlined in the diagram.

Figure 7.2 shows the importance of surface conditions and supply processes to aeolian phenomena in cold areas. Aeolian activity which is unhindered by surface constraints occurs within a very narrow combination of wind speeds and water contents. The

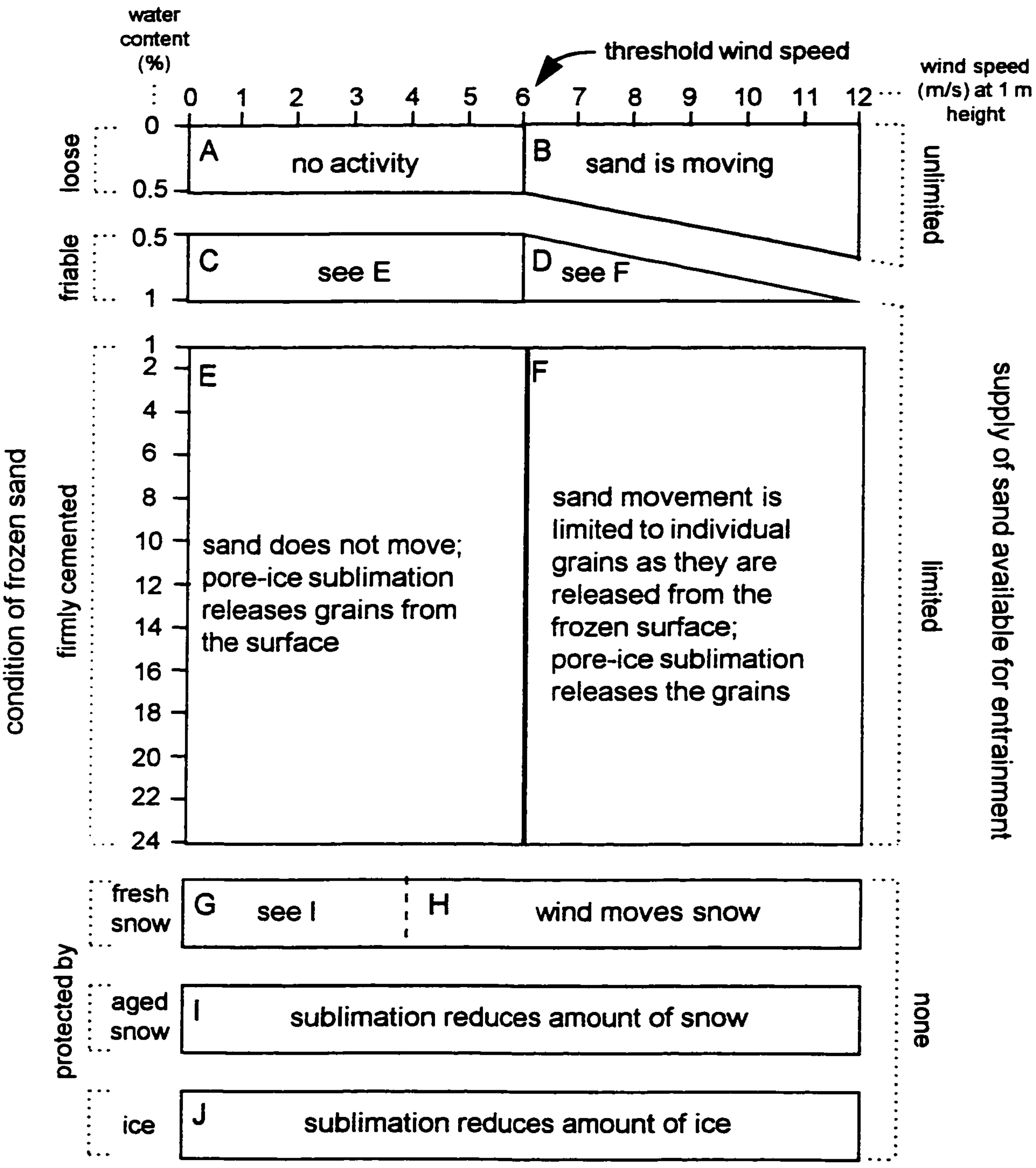


Figure 7.2 Cold-aeolian processes determined by moisture and wind

remainder of cold-aeolian activity is constrained to varying degrees by surface conditions. Supply mechanisms are vital to the existence of sand movement.

7.4 Potentials for Cold-Aeolian Movement

The pervasiveness of surface constraints on cold-aeolian processes prompts a different way of looking at condition-process interactions. If one neglects, for the moment, whether sand is or is not moving, one can view the frozen surface in terms of potentials for movement. The potentials suggest the likelihood of movement from a surface at a given moment in time and can correspond to a) the time needed before sand on that surface would be able to move or b) the amount of sand that is likely to move from the surface if movement began immediately. Movement potentials indicate how easily surface constraints in a particular area can be overcome.

Potentials for movement are illustrated by colour in figure 7.3. Colour intensity reflects variations in potential for movement, whereas different colours differentiate between unlimited, limited and no supply of sand available for movement. Movement potentials mean different things in each of these categories.

When the sand supply is unlimited, there are no surface constraints and the potential for movement is based solely on wind speed over the surface. Winds that exceed the critical threshold can cause immediate movement of sand. The potential for movement, therefore, increases as wind speeds increase.

As frozen sand cementation increases, sand supply becomes limited and the potential for movement decreases. Under these conditions, entrainment is a two-step process which requires sublimation to remove pore-ice bonds from the sand grains before movement takes place. The potential for movement decreases as surface cohesion (measured by water content) increases. Wind speed also affects the potential for movement by its influence on pore-ice sublimation. At any water content, higher wind speeds result in greater potential for movement.

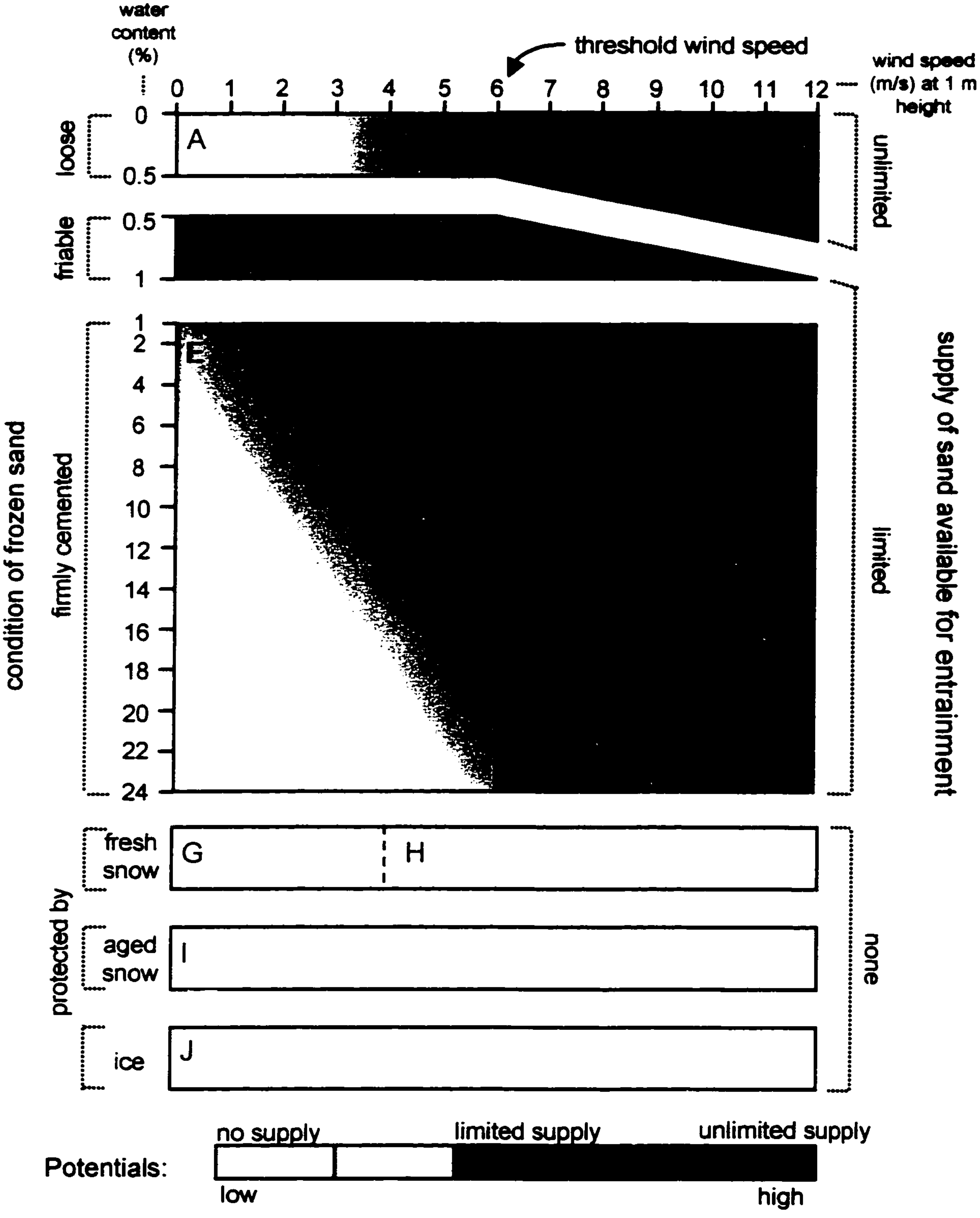


Figure 7.3 Cold-aeolian potentials determined by moisture and wind

Potentials for movement decrease further when the surface is covered by snow or ice and immediate movement is not possible. Under these conditions, entrainment could be described as a three-step process: first the snow or ice must be removed from the frozen surface, then the surface can undergo pore-ice sublimation, and finally the released sand grains can move. In this area of figure 7.3, potentials indicate how close the underlying sand is to exposure. The potentials depend on the depth of the protective cover and its density. Surfaces have greater potential when higher winds increase sublimation-drying. Fresh snow can be blown off the surface by strong winds, and therefore it has a greater potential for disappearance than aged snow or ice. The potentials indicated for protected surfaces are superimposed potentials, and the underlying frozen ground fits into a new category of potentials after the protective layer is gone (i.e., the green or red categories of figure 7.3).

The influence of temperature on potential for movement is illustrated in figure 7.4 where increasing density of shading indicates increasing potential for movement. Potentials for movement increase as temperatures increase. For clarity of presentation, the potentials of figure 7.4 were not added to figure 7.3.

In figure 7.5, potentials for movement based on surface conditions have been applied to the Presqu'ile Beach profile for a specific day in January 1997. The diagram illustrates two areas from which sand movement is most likely to occur: a 13-metre width near the icefoot and a 14-metre width in the middle of the beach. The area with the least potential for movement is the 22-metre stretch of ice between the two

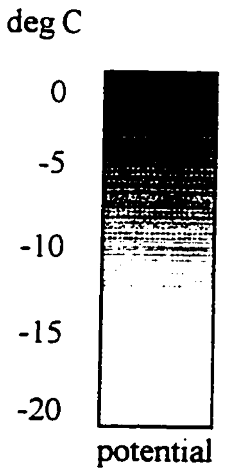


Figure 7.4 Temperature and potential for movement

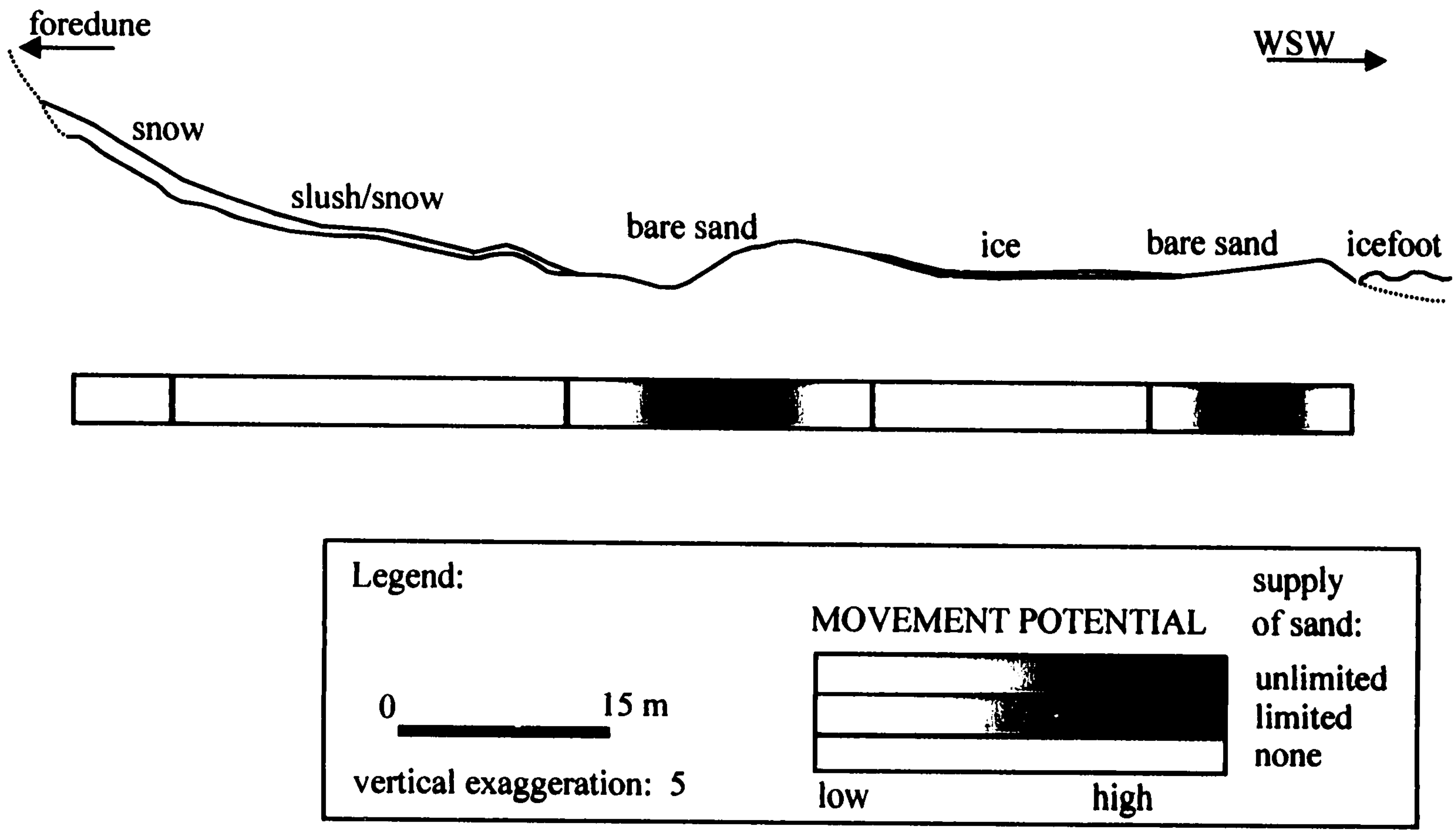


Figure 7.5 Presqu'ile Beach profile with potentials for movement, 16 January 1997

exposed sections. The study area was roughly 60-metres long, and the beach profile of figure 7.5 is representative of conditions across the study area. Therefore, limited sand movement was possible from approximately 1620 m^2 compared to 3480 m^2 of beach which were protected by snow and ice and had very low potential for movement.

7.5 The Cold-Aeolian Computer Simulation

The computer simulation combines variables, boundaries, interrelationships, predicted activities and equations into a comprehensive model of cold-aeolian activity. The simulation uses keyboard or file inputs of local conditions to predict what type of activity will occur, how much sand will be released from the surface by pore-ice sublimation, and how much sand will move from the area. The model can be applied to single time periods or many consecutive periods. One of the advantages of the computer simulation is that it repeats calculations quickly and efficiently. The computer model also does a better job of integrating the many variables that control cold-aeolian activity than a two-dimensional diagram.

7.5.1 The Algorithm

The cold-aeolian algorithm is a logical sequence of steps which provides the structure for the computer simulation. The simulation procedure turns inputs of local conditions into descriptions of what aeolian activity is occurring at the surface, how much sand is released from the frozen surface, and how much sand is moving from the surface. The algorithm is illustrated by a flow chart (figure 7.6) and the steps are described below. The terms *model* and *algorithm* refer to steps of calculation and prediction, whereas *simulation* refers to an actual application of the model incorporating one or more periods. A *period* is a 12-hour block in which local conditions are reduced to single values (often averages) and for which the model produces a single estimate of loose sand production, among other things.

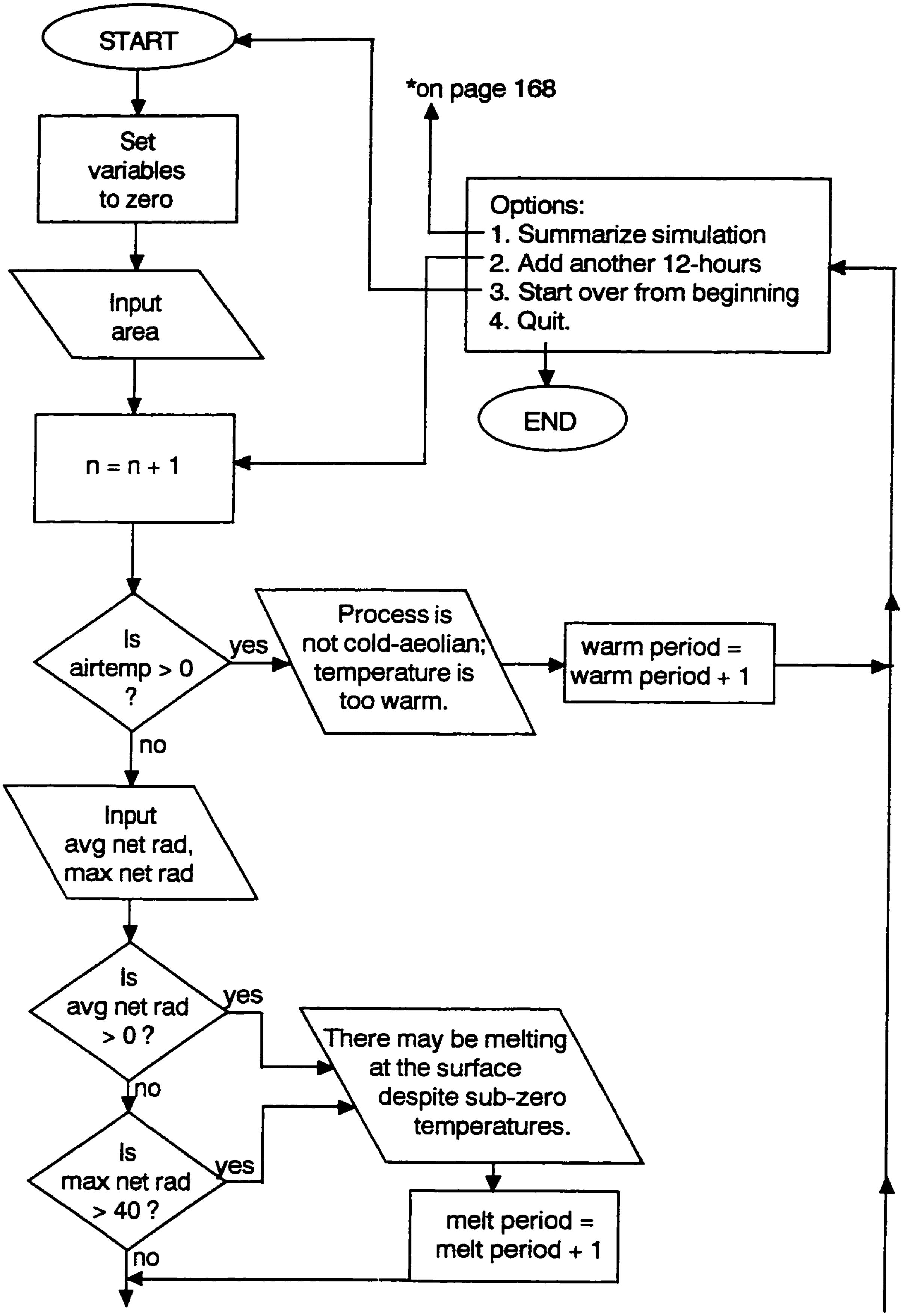


Figure 7.6 Flow chart for cold-aeolian computer simulation

The first steps of the algorithm set the scene for the simulation. Simulation totals--records of how much loose sand is on the surface, how much sand has moved, how many times this has happened and so on--are set to zero as each new simulation is run. The model contains a default area of a square metre but there is opportunity to specify a larger area to be applied to calculations of loose particle production and sand transport. A variable *n* is used to keep track of the number of 12-hour periods considered in sequence. The number of periods is up to the user, and *n* increases by 1 each time a new period has begun.

The option box represents the end of each period but is illustrated here because it closes many loops in the simulation. Several options are given each time the computer has completed a prediction. Another 12-hour period can be added to the simulation to investigate continuing processes in the same area (option 2). When no additional periods need to be considered, a simulation summary is available (option 1). The remaining choices abort the simulation by starting over (option 3) or exiting the program (option 4).

The model uses air temperature to determine whether the processes are cold-aeolian. Above $0^\circ C$, melting occurs and an assumption of cold-aeolian processes is no longer valid. When these conditions exist, the model outputs a statement that the processes are not cold-aeolian because the temperature is too warm. The warm period is recorded by adding 1 to the appropriate variable. The rest of the model does not apply and the user is sent to the options of continuing with another 12-hour period, etc. When air temperature is below $0^\circ C$, cold-aeolian processes are assumed and the model goes to the next stage.

Net radiation data provide a crude way of checking whether an assumption of drying by sublimation is valid. The user is asked to provide both average and maximum net radiation for the period. During winter months, values for net radiation are usually negative as the surface emits more radiation than is received from the low-angle winter sun. The infrequent positive values may correspond to melting at the surface (even below $0^\circ C$) when solar radiation is absorbed by the ground. Intervals of solar radiation intense

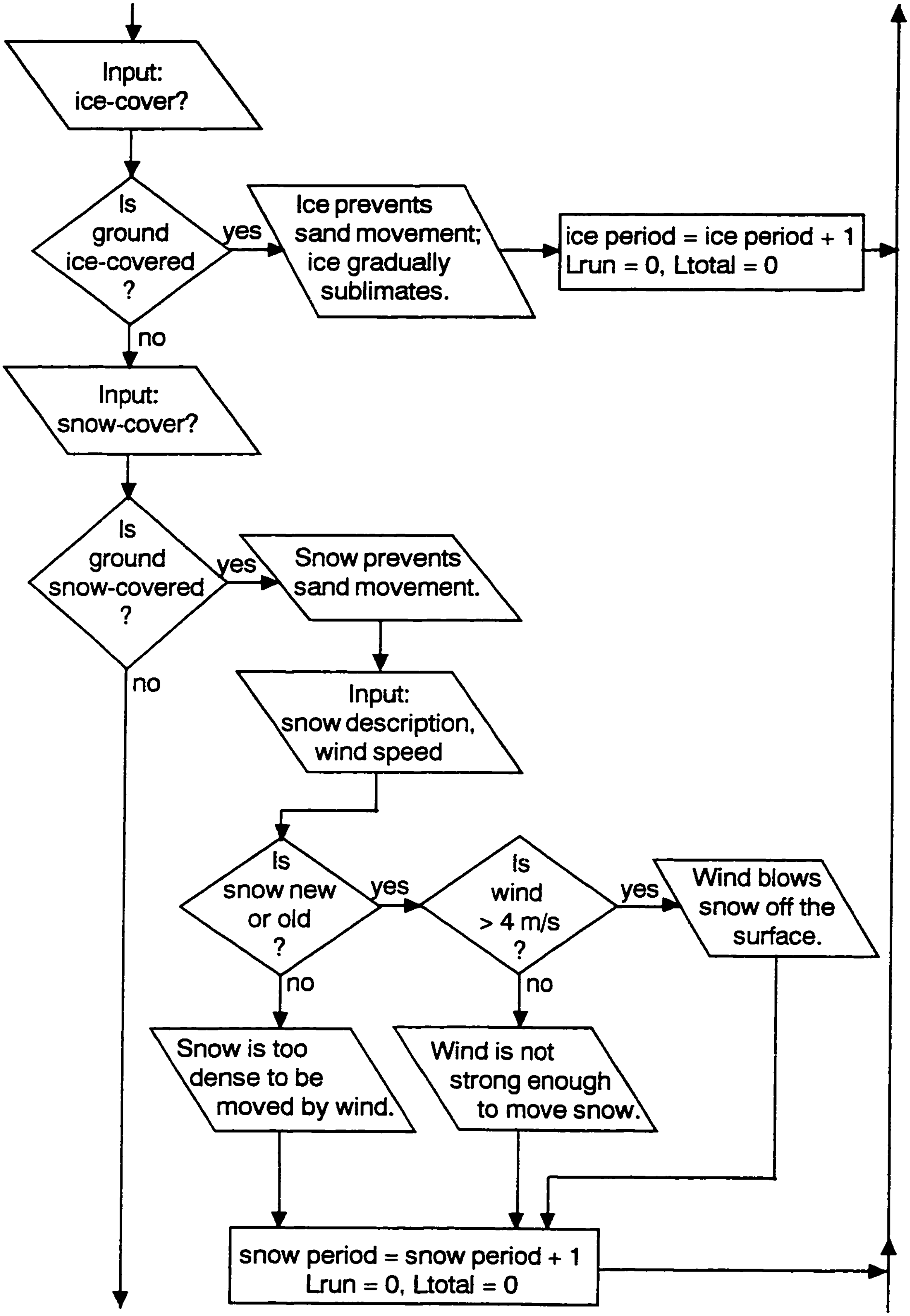


Figure 7.6 continued...

enough to cause surface melting are restricted to clear middays when the sun is at its peak. Short intervals may not influence 12-hour averages of net radiation but will show up as high positive values in the daily record. When the model encounters average net radiation above 0 W/m^2 or maximum net radiation above 100 W/m^2, a cautionary note is produced. The printed warning indicates that at some time during the period melting may have occurred at the surface and caused the processes to be not strictly cold-aeolian. After recording a possible melt period, the model proceeds as usual (that is, no further action is taken by the model with respect to the possible melting).

A layer of surface ice prevents aeolian processes from acting on the frozen sediment. Sand movement is effectively halted as the frozen sand is protected from wind action by the surface ice. The ice-layer can be reduced in size and depth by sublimation-drying during cold periods and melting/evaporation during warm periods. When the user indicates that surface ice is present, the model prints a notice that sand is prevented from moving by the ice. Rates of ice disappearance are not calculated, but asking the same question during the next period gives a rough measure of ice longevity. A period of ice is recorded and loose sand totals are set to zero because any loose sand that was available in the previous period is now immobilized under the ice. The model returns to the start of the next period.

With no ice present, snow-cover is investigated. Snow has a similar effect to ice in that it blankets the surface and protects underlying sand from movement by wind. Unlike surface ice, snow can be blown off the surface if the winds are sufficiently strong. Inputs of snow type and wind speed are examined by the model to produce predictions concerning the movement or non-movement of snow. A period of snow is recorded. Once again loose sand totals are set to zero because of the addition of precipitation and the model returns to the start of the next period. When no snow-cover is present, the model bypasses the steps of requesting and assessing wind speed and snow condition.

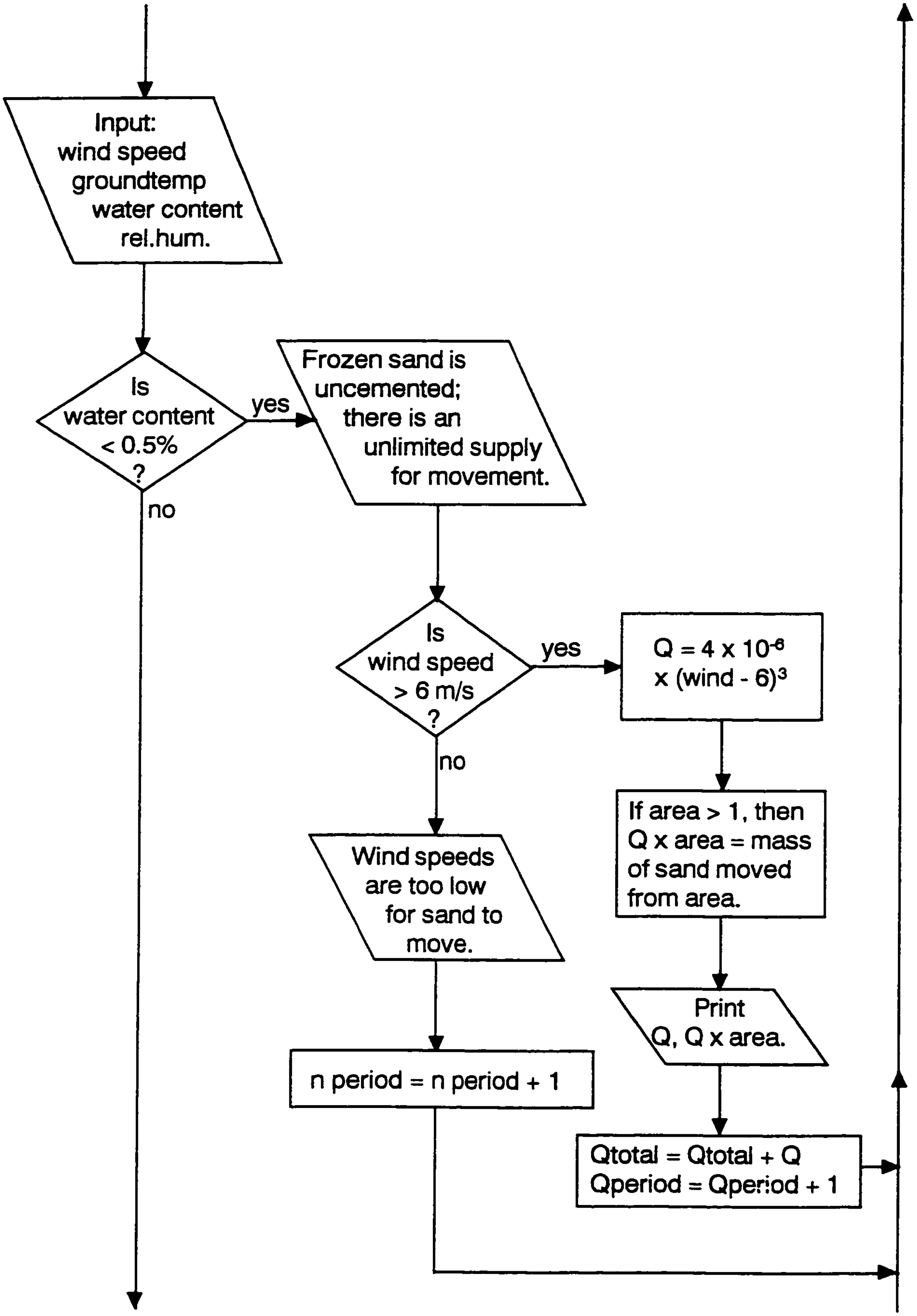


Figure 7.6 continued...

The model requires data on local conditions once it has established that processes are cold-aeolian and snow or surface ice are not present. Inputs of wind speed, ground temperature, frozen sand water content, and relative humidity are used to determine simulation outcomes. Wind speed is the 12-hour average measured at a height of 1 metre above the surface. The 12-hour average ground temperature is measured approximately 4 centimetres below the ground surface. Water content should be measured in the top few centimetres of the frozen sand. Relative humidity is also averaged over the 12-hours.

Exposed frozen sand is uncemented and available for movement when the surface water content is less than 0.5% by mass. The sand supply for aeolian processes is unlimited and movement depends on the speed of the wind. If the measured wind speed is below the calculated threshold of 6 m/s, sand will not move and a period of no movement is recorded. When wind speeds exceed the threshold, the quantity of transported sand (Q) can be calculated based on wind. Equation 7.4 gives the amount of sand moved in kg m^{-2} $(12\text{-hour})^{-1}$. The amount can be multiplied by the size of the study area for total movement. Sand movement is printed to the screen and added to the total sand moved during the simulation. A period of sand movement is recorded.

An additional feature of the computer simulation (not illustrated in the flow chart) is that it accounts for sand which has been released from the frozen surface during previous periods. When all of the frozen sand is uncemented, the amount of sand that has been previously released from the surface is no longer important. The model sets totals for 'released' sand back to zero. A statement to that effect is printed on the screen.

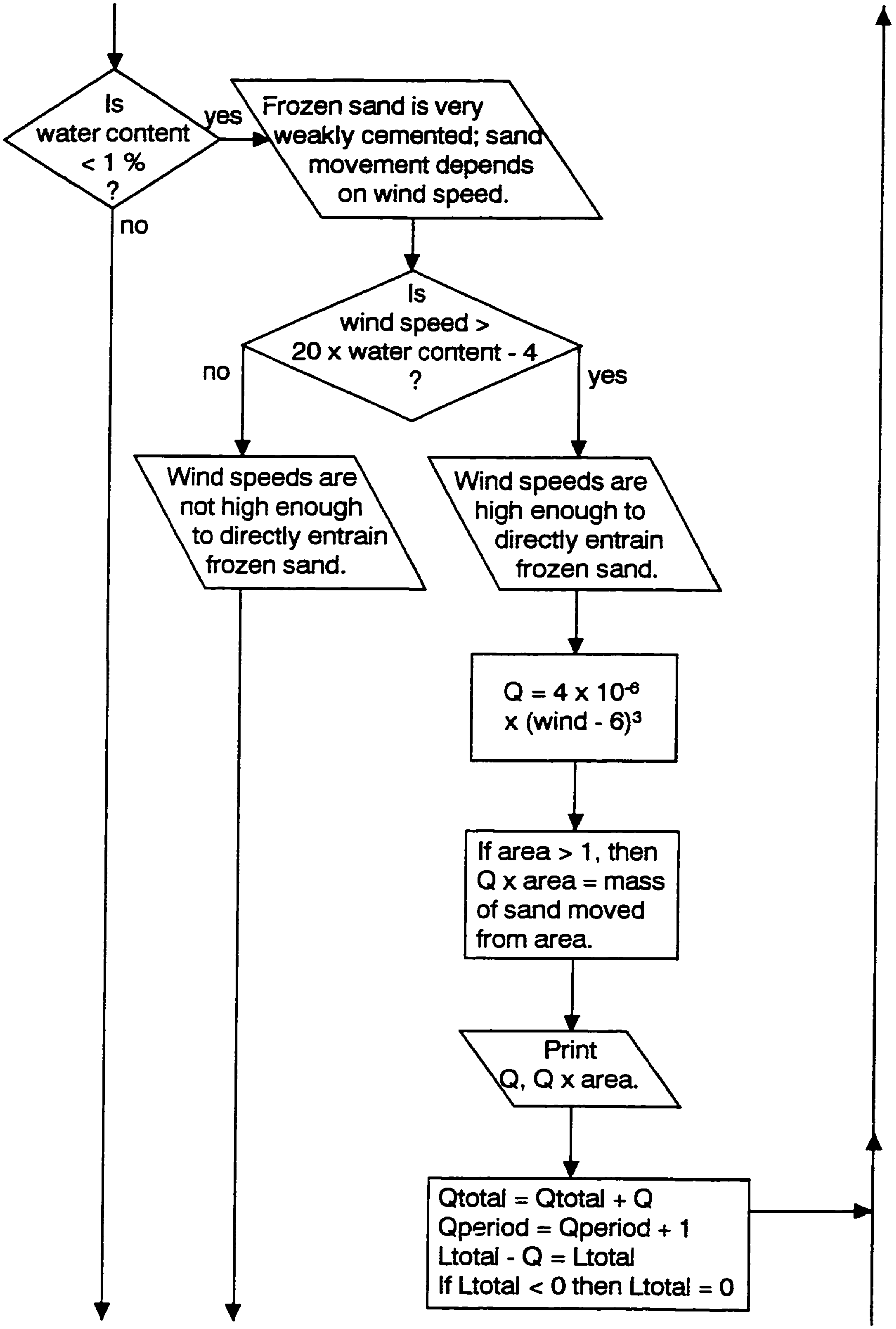


Figure 7.6 continued...

When the water content of frozen sand is between 0.5% and 1%, exposed sand is very weakly cemented and its movement is contingent upon wind speed. Whether sand can be directly entrained by the wind depends on the strength of the wind relative to the water content. For the purpose of the simulation, the boundary between direct entrainment and supply-limited transport is set by the following equation

$$threshold = 20w-4 \tag{7.6}$$

where w is water content in percent. When measured wind speeds are below this threshold, particles must be released from the frozen surface before entrainment occurs. The model proceeds to calculate particle release on the following page of the flow chart (page 166).

When the measured wind speeds exceed the new threshold, sand grains can be directly entrained by wind from the frozen surface. Equation 7.4 calculates the amount of sand which is moved by wind from the surface. The result per square metre can be multiplied by the size of the study area for total movement. Movement totals are printed to the screen and added to the total sand moved during the simulation. A period of sand movement is recorded.

When previously released sand is present, it will be entrained first. The amount of previously-released sand cannot simply be added to the total sand moved (Q) because movement is transport-limited instead of supply-limited. The total sand movement is determined by the wind as calculated in equation 7.6 and cannot be increased. However, removal of the previously-released sand from the surface first decreases the store of released sand for subsequent periods. The sand which has moved is subtracted from the loose sand at the surface to determine how much loose sand remains.

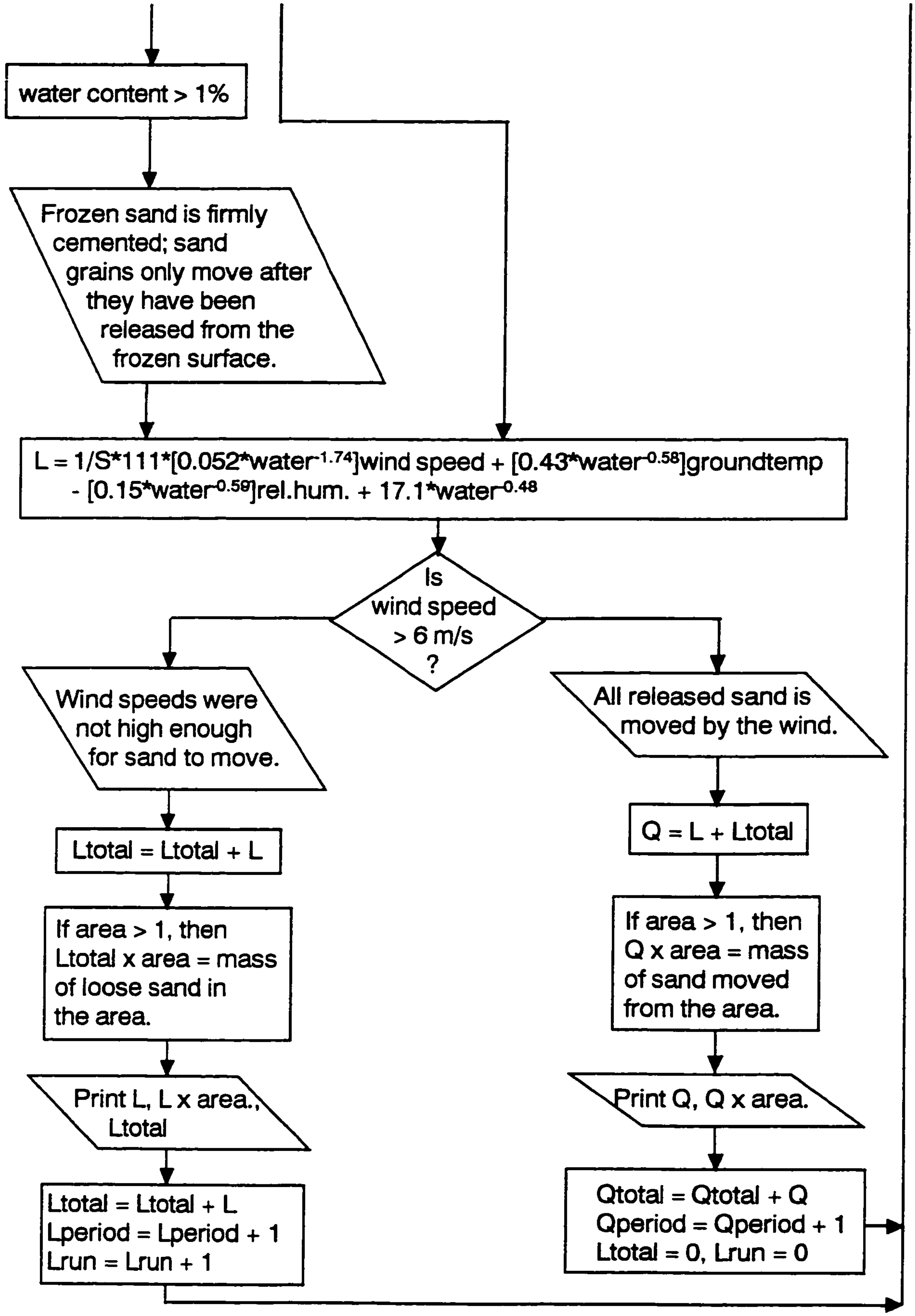


Figure 7.6 continued...

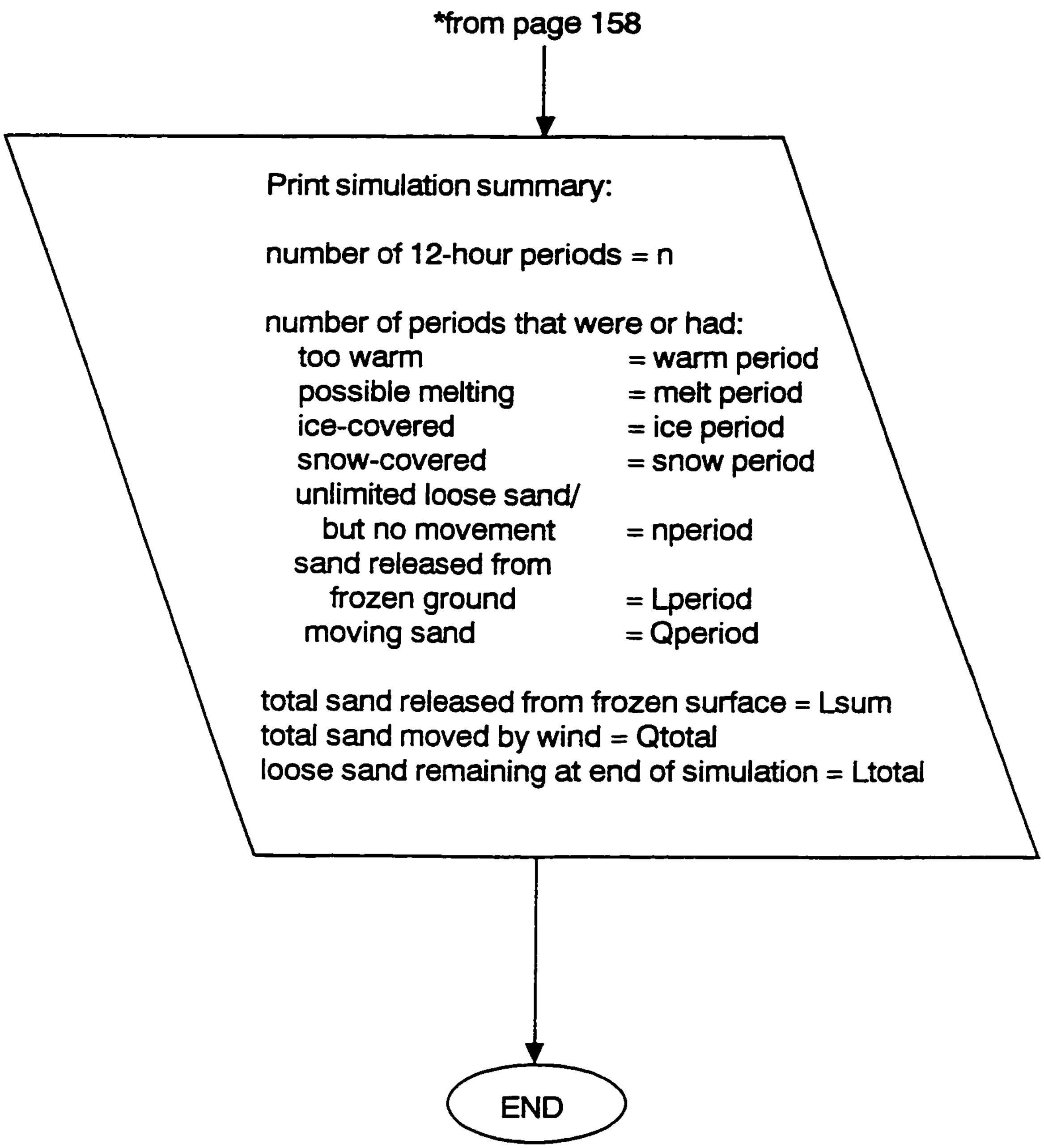
S	depth of dried layer	weight of dried sand (kg/m^2)
1	< 1 cm	< 14
2	1 - 2 cm	14 - 28
3	2 - 3 cm	28 - 42
4	> 3 cm	> 42

Table 7.2 Dried sand depth, weight and S

Exposed frozen sand is firmly cemented when the water content exceeds 1%, and aeolian entrainment is only possible when particles have been released from the frozen surface. The amount of loose sand produced in a 12-hour period is calculated from equation 6.7. The calculation is multiplied by an additional term, 1/S, to include the decrease in loose particle production that accompanies prolonged surface drying with no sediment removal. Values for S are given in table 7.2. Whether the released sand will move or not depends on how the measured wind speed compares to the threshold wind speed of 6 m/s.

When the measured wind speed is below 6 m/s, the released sand does not move. The amount of loosened sand per square metre can be multiplied by the size of the study area to find the total amount of loose sand produced. Loose sand totals per m^2 and for the entire area are printed to the screen as well as a cumulative loose sand totals when applicable. A period of loose sand production is recorded and a value of 1 added to a running total of sand release without transport.

When the measured wind speed exceeds 6 m/s, the sand released from the surface is transported by the wind. Sand transport equals the loose sand collected on the surface from previous periods as well as the new 12-hour total. The amount of transported sand can be multiplied by the size of the area to find the total amount of sand moved. The amounts of sand transported per square metre and for the entire area are printed to the screen. The amount of sand transported is added to the total for the simulation and a period of sand movement is recorded. Because all loose sand on the surface has been transported, the model sets the total loose sand on the surface and the running total of loose sand periods back to zero.



Print simulation summary:

number of 12-hour periods = n

number of periods that were or had:
too warm = warm period
possible melting = melt period
ice-covered = ice period
snow-covered = snow period
unlimited loose sand/ but no movement = nperiod
sand released from frozen ground = Lperiod
moving sand = Qperiod

total sand released from frozen surface = Lsum
total sand moved by wind = Qtotal
loose sand remaining at end of simulation = Ltotal

Figure 7.6 continued

When the the simulation has been run for the desired number of time periods, a simulation summary can be printed to the screen. The summary indicates how many twelve-hour periods were covered by the simulation and the number of periods which had various conditions. It should be noted that the last two entries on the list can occur simultaneously. The summary also indicates the total amount of sand released from the frozen surface, the total amount of sand transported during the simulation, and the loose sand remaining on the surface at the end of the simulation.

7.5.2 COLDAEOL.BAS: The Computer Program

The cold-aeolian simulation has been put into a computer program called COLDAEOL.BAS (see appendix C and disk). The program is written in QBasic and can be run on any PC which supports QBasic. COLDAEOL.BAS converts simple data into predictions of how much sand is moving and what types of activity are ongoing in designated areas. The program also provides an opportunity to experiment with how different conditions affect cold-aeolian processes. Simulation length is flexible as the program is able to investigate a single period or an unlimited number of periods.

COLDAEOL.BAS accepts input data from the keyboard or from a separate file. Data which are placed in a separate file must be in a specific order and separated by commas. Only final totals from the simulation are printed when a file of data are used.

7.6 An Application of the Cold-Aeolian Simulation

Six days from January 1997 have been chosen to demonstrate the cold-aeolian simulation in action. Data for the demonstration (table 7.3) were taken from Presqu'ile Beach microclimate data and daily beach observations. The daily observations indicated that the exposed sand during the six days was limited to a narrow strip near the ice-foot. The exposed area was approximately 3 metres wide by 60 metres long for a total area of 180 m^2. The water content of this sand was near saturation and a percentage of 24 has been assigned to each of the time periods. The data were put into COLDAEOL.BAS via the keyboard rather than a file so that statements for each 12-hour period could be printed.

date	end of period	air temp	avg net rad	max net rad	ice	snow	wind speed	grnd temp	water cont.	rel. hum.
5 Jan 97	1200	5.0	24	43	no	no	2.0	0.2	24	99
	2400	3.5	1	36	no	no	8.2	0.2	24	86
6 Jan 97	1200	-0.4	1	77	no	no	11.2	0.1	24	73
	2400	-1.8	10	102	no	no	10.8	-0.8	24	73
7 Jan 97	1200	-6.0	-10	49	no	no	4.0	-1.7	24	78
	2400	-7.2	-20	143	no	no	6.6	-3.3	24	66
8 Jan 97	1200	-10.8	-22	146	no	no	4.2	-5.7	24	59
	2400	-8.0	-23	150	no	no	3.8	-3.5	24	55
9 Jan 97	1200	-11.7	-28	46	no	no	1.9	-5.9	24	69
	2400	-9.4	6	63	no	no	3.1	-3.1	24	88
10 Jan 97	1200	-1.0	-2	8	no	yes	8.0	-0.7	24	86
	2400	-2.9	-3	8	no	yes	9.5	-0.2	24	92

Table 7.3 Selected microclimate and surface conditions for Presqu'ile Beach during 5-10 January 1997

As the simulation began, model interaction with the two periods from 5 January 1997 were similar and brief. The computer requested air temperature in degrees Celsius and, upon receiving the values of 5.0 and 3.5 respectively, returned a statement that

```
In this 12-hour period the processes are not cold-
aeolian because the temperature is too warm.
```

No further information on conditions was required and the program moved on to the next time-period.

More simulation activity occurred for the two periods on 6 January. The model made no response to the air temperatures which were below 0°C, but the following statement was returned after the positive values for average net radiation were entered:

```
There may be melting of surface pore ice despite
below-zero temperatures.
```

The next response by the computer came after the remaining data on local conditions were entered for each day. The following message was printed on the screen for the first half of 6 January:

```
Frozen sand is firmly cemented by pore ice.  Sand
grains are only available for movement when they have
been released from the surface by pore-ice
sublimation.

During this 12-hour period, average wind speed
exceeded the threshold necessary for aeolian
transport and all the loose sand was removed from the
area.

1.7 kg of sand per square metre were released from
the surface by pore-ice sublimation for a total of
311 kg over the 180 square metre area.

All of the released sand was moved by wind.
```

For the second half of 6 January, an identical message was printed on the screen with the exception of totals of 1.6 and 289 kg of sand released per square metre and 180 m^2, respectively.

Wind speeds for the first half of 7 January did not exceed the threshold of 6 m/s, and the simulation noted the change. A message that

```
During this 12-hour period, wind speeds were too low
for sand to move.
```

preceded the totals of 0.8 kg of sand released per square metre for a total of 151 kg over the 180 m^2 area.

Wind speeds increased later on 7 January and the model indicated that loose sand was once again being removed by the wind. During this time-period 1.3 kg/m^2 of sand was released from the surface (236 kg/180 m^2). The computer message concluded that

```
There were already 0.8 kg of loose sand per square
metre on the surface; therefore, 2.2 kg per square
metre were removed by the wind over the 12-hour
period for a total of 388 kg over the 180 square
metre area.
```

The message indicated that the wind had removed the loose sand produced during the current time period plus the sand which had been released from the surface during previous time period(s) but had not yet been transported.

Over the next two days, wind speeds remained below the threshold for sand transport, but pore-ice sublimation continued to release sand grains from the frozen surface. Table 7.4 shows the amount of sand released and accumulating on the surface for all the simulation periods. The last column shows the build-up of loose sand during 8 and 9 January. The total released sand of 3.5 kg/m^2 would form a dried layer with a thickness of 2-3 mm on the surface.

n	day	end of period	released sand (kg/m^2)	released sand still on the surface (kg/m^2)
1	5 Jan 97	1200	-	-
2		2400	-	-
3	6 Jan 97	1200	1.7	0
4		2400	1.6	0
5	7 Jan 97	1200	0.8	0.8
6		2400	1.3	0
7	8 Jan 97	1200	1.2	1.2
8		2400	1.5	2.7
9	9 Jan 97	1200	0.6	3.3
10		2400	0.2	3.5
11	10 Jan 97	1200	-	0
12		2400	-	-

Table 7.4 Simulation results

Winds became stronger again during the early part of 10 January but were accompanied by snow. The simulation's response to the snowfall was

```
Snow cover protects the frozen ground and no aeolian
movement of sand occurs.
```

When the wind speed of 8 m/s was entered and a snow category of "freshly fallen snow, dry or fluffy" was selected, the model further explained that

```
Blowing snow occurs as wind moves snow from the area.
```

Furthermore, the snow had implications for the layer of loose sand that had formed on the surface over the previous couple of days. The model indicated that

```
Previously, 3.5 kg of sand per square metre were
released from the frozen surface by pore-ice
sublimation.  Snow, ice, and warm periods change the
condition of the surface and can add moisture through
vapour transfer, melting and refreezing, and rain.
The amount of 'released' sand will not be saved for
future calculations.
```

The model was saying that when the snow disappeared, it would be unlikely that the layer of dried sand was still dry. Therefore the cumulative total of released sand was being set back to zero and the drying process would have to begin anew when the snow disappeared.

The second half of 10 January was similar to the first. For this period a snow category of "older snow, wet, heavy, firmly packed or dense" was chosen because the snow had been on the surface for a number of hours already. Despite wind speeds of 9.5 m/s, the simulation indicated that

```
Winds are not strong enough to move snow from the
area, but sublimation of snow occurs.
```

There was no need for the model to comment on loose sand because the cumulative total remained at zero.

The following session summary was printed on the screen upon termination of the simulation:

```
*****************Simulation Summary****************

Total number of periods:  12  Area:  180 m2

Conditions                    Number of Periods

too warm                                2
possible melting at surface             7
ice-covered                             0
snow-covered                            2
unlimited loose sand but no movement    0
sand released from frozen ground        8
sand moving                             3

Total sand released from the frozen surface:  1618 kg

Total sand moved by the wind:  988 kg

Loose sand remaining at end of simulation:  0 kg

*****************************************************
```

Sand movement occurred in three of the twelve periods and removed 988 kg of sand from the 180 m^2 area. This compares to eight periods over which 1618 kg of sand were released from the frozen sand. The summary notes that possible melting of the surface may have occurred during 7 of the 12 periods. To round out the totals, 2 periods were too warm for cold-aeolian processes and the surface was covered with snow in two other periods.

7.7 Summary

The cold-aeolian simulation integrates a lot of data into a format which captures the essential information during specific periods and predicts activity, sand release and sand transport. In temperate latitudes, cold-season conditions can be varied and complex, ranging from melting and warm temperatures to cold and blustery conditions in less than 24 hours. Potentials for aeolian erosion and spatial variations within designated areas can change just as fast. The program COLDAEOL.BAS is a tool for tracking aeolian activity and sand movement throughout variations in local conditions and for making predictions about different combinations of variables. Model inputs are fairly simple: air temperature, net radiation, observations of snow and ice cover, wind speed at a height of 1 metre, surface water content, ground temperature 3-4 cm below the surface, and relative humidity. Model conclusions range from the simple to the complex--from statements that movement is not possible because of snow or ice to detailed quantities of sand released and transported.

The arrangement of information about cold-aeolian activity is just as important as the quantitative predictions. Diagrams such as figure 7.2 and 7.3 define interactions between variables and boundaries between processes. The conditions and processes may be dynamic and constantly changing, but certain relationships are pervasive. Thus, transport-limited sediment movement can only occur when water contents lie in a very narrow, low range and supply-limited transport is the norm. Surface cover may range from a thin but tenacious layer of ice to waist-high drifts of snow but the net result is that underlying sediment is protected from wind erosion. While the relationships provide the structure for effective prediction and simulation, they also serve as a framework for understanding and continued investigation.

Chapter Eight

FIELD MEASUREMENTS AND THE COLD-AEOLIAN MODEL

You can observe a lot just by watching.
Yogi Berra

Field measurements quantify cold-aeolian activity at Presqu'ile and enable testing of the computer model COLDAEOL.BAS. The field data were collected on the Presqu'ile Beach between 15 December 1996 and 15 March 1997. The measurements show timing, patterns and amounts of sand movement during the cold season. The detailed and quantitative observations are unprecedented in the study of cold-aeolian phenomena. Microclimate data and beach measurements also permit model predictions for equivalent time periods. The predictions of sand movement are compared to field measurements of deflation and transport in an assessment of model accuracy.

8.1 Field Measurements of Sand Movement

Sand movement over the Presqu'ile Beach was quantified by means of regular beach observations, erosion pins, and winter sand traps. Daily observations recorded the timing of sand movement and the presence of factors which inhibited movement. Frozen surface deflation was measured in the elevation changes at erosion pins. Sand traps captured sand moving across the frozen beach to provide information on direction of movement and rates of transport.

8.1.1 Daily Observations

The daily record of Presqu'ile Beach observations contains many entries that are directly relevant to cold-aeolian activity. An abridged record (table 8.1) contains direct observations of sand movement, a summary of beach conditions, and average wind speeds for the same time periods. Aeolian activity is indicated by notations that sand and/or snow was moving and by the presence of sand on top of snow/ice as evidence that sand movement had taken place. Remarks about mild temperatures, rain and snow/ice cover

date	comments	aeolian activity	1-m wind speeds
12 Dec 96	dry sand deposits by dunes and shallow deposits (with ripples) scattered across beach	occasional sand movement across beach to water	3-4 m/s
13-18 Dec 96	warm/rain		
19 Dec 96	shallow dry deposits and occasional ripples	individual grains moving	3-7 m/s
20 Dec 96	ripples and dry sand deposits in front of and on dunes	sand moving at all times	6-10 m/s
21 Dec 96		sand moving	6-9 m/s
22-24 Dec 96	warm/rain		
25-26 Dec 96	-- no observations --		
27-29 Dec 96	beach is snow-covered		
30 Dec 96	some exposed frozen sand with dry sand deposits and ripples		2-3 m/s
31 Dec 96 - 5 Jan 97	beach is snow-covered - milder/rain		
6 Jan 97	beach overwash frozen up to sand-trap site (no icefoot)	sand moving; saltating grains observed above 1.5 m	10-12 m/s
7 Jan 97	some exposed frozen sand (icefoot has formed)	snow and sand moving	5-9 m/s
8 Jan 97	some exposed frozen sand; dry sand caught in small depressions of rough ice	sand moving infrequently	3-6 m/s
9 Jan 97	snow		

Table 8.1 Cold-aeolian observations and measured wind speeds on Presqu'ile Beach, December 1996 through March 1997.

date	comments	aeolian activity	1-m wind speeds
10 Jan 97	sand visible on top of snow	snow and sand moving	8-11 m/s
11 Jan 97	some exposed patches of frozen sand		7-8 m/s
12 Jan 97	some exposed sand; sand is visible on snowdrifts	snow and sand moving	7-9 m/s
13 Jan 97	-- no observations --		4-6 m/s
14 Jan 97	entire beach looks brown/sandy despite snow drifts over most of the area; the windblown sand has frozen into depressions on the snow		6-8 m/s
15 Jan 97	crusts of frozen sand on snow are 1-3 cm thick		3-6 m/s
16-17 Jan 97		blowing snow	6-11 m/s
18 Jan 97	additional sand deposits over snow and ice		2-3 m/s
19-20 Jan 97	snow; sand on top of drifts	blowing snow	5-9 m/s
21 Jan 97	some exposed sand		1-2 m/s
22 Jan 97	milder temperatures		
23 Jan 97	some exposed frozen sand with dry sand deposits		3-4 m/s
24 Jan 97	sand moved overnight from east to west; afternoon snow; beach snow-covered by evening	infrequent movement in morning; blowing snow and sand in afternoon	--
25 Jan 97	dense soggy layer of snow over beach		9-13 m/s

Table 8.1 continued...

date	comments	aeolian activity	1-m wind speeds
26 Jan 97	small exposed patches		1-4 m/s
27 Jan 97	small exposed patches have shallow dry deposits on them		2-3 m/s
28 Jan 97	beach completely snow-covered		5-7 m/s
29-31 Jan 97	small exposed patches		1-5 m/s
1-17 Feb 97	beach completely snow-covered		1-7 m/s
17-18 Feb 97	tiny exposed patches		1-8 m/s
19-21 Feb 97	warmer/melting/rain		
22 Feb 97	very windy; temperatures dropped in late morning and by late afternoon there was substantial ice-cover over beach	chunks of ice blown from surface; sand moving over beach and ice	9-15 m/s
23 Feb 97	areas of exposed sand have 1-2 mm of dry sand on top		0-3 m/s
24 Feb 97	berm is exposed with patches of dry sand and snow; sand is visible on snow and ice to app. 30 m downwind of berm		3-9 m/s
25 Feb 97	berm is exposed with 1-2 mm of dry sand on top; snow began at 10:30 am, wind picked up at 11:37 am, berm cleared of snow by 12:07 pm, beach cleared of most snow by evening with some dense snow/sand patches remaining	snow and sand moving blowing sand	0-1 m/s 6-10 m/s
26 Feb 97	milder/rain	sand moving before thaw	4-8 m/s

Table 8.1 continued...

date	comments	aeolian activity	1-m wind speeds
27 Feb 97	beach thawed and soggy		
28 Feb 97	some exposed frozen sand		0-3 m/s
1 Mar 97	-- no observations --		
2 Mar 97	warm		
3 Mar 97	some dry sand on exposed beach; midday thaw	occasional sand movement from east to west	2-3 m/s
4 Mar 97	warmer/precipitation		
5 Mar 97	thin layer of ice over all		
6 Mar 97	beach mostly snow-covered with no evidence of blown sand around exposed areas		4-9 m/s
7 Mar 97	beach snow-covered with larger exposed patches; significant amounts of sand on snow--thicker near exposed areas and thinning towards dunes		4-7 m/s
8-9 Mar 97	-- no observations --		0-4 m/s
10-11 Mar	snow/rain/milder		
12 Mar 97	ripples of dry sand on surface in morning; midday thaw	sand moving in morning	5-7 m/s
13 Mar 97	midday thaw		3-5 m/s
14 Mar 97	snow in morning then mild	snow and sand moving from east to west	7-11 m/s
15 Mar 97	layer of ice over all surfaces		

Table 8.1 continued.

correspond to periods and areas of aeolian inactivity. The presence of exposed frozen sand is noted because of its importance as a source area for aeolian sediments. Dry sand indicates that sublimation-drying had occurred; dried sand in shallow deposits or ripples indicates that some sand movement had taken place. The final column in table 8.1 contains the range of average wind speeds (at a height of 1 metre) for the period of activity or inactivity.

8.1.1.1 Winter Sand Movement

The beach observations captured five strong wind events during the 1996-1997 winter:

1. Sustained winds over a three-day period in December (19-21) moved sand from the exposed frozen beach to the foredunes. The absence of snow or ice on the beach at this early winter date contributed to the substantial amounts of sand moved.
2. A stronger wind event was observed in early January (6-8). Winds of 10-12 m/s (at a height of 1 metre) transported grains at heights of 1.5 to 2 metres and plastered snow to the tops of 4-metre posts. In the absence of shore-fast ice, lake water was driven up to 40 metres onshore by the winds. As the water froze, it formed smooth layers of ice over the frozen sand and protected a substantial area from deflation by wind.
3. A series of winter squalls in mid-January (10-12) brought more than 20 cm of snow and winds between 7 and 11 m/s. Both snow and sand were moved inland by the wind. When the winds died down, snowdrifts with depths between 3 and 20 cm extended from mid-beach to the foredune and appeared brown from the superimposed layer of sand. Larger deposits of wind-blown sand had collected between snow-drifts and most of the sand had refrozen to form crusts that were up to several centimetres thick.
4. Violent winds on 22 February ripped layers of ice from the beach and shattered them as they blew inland. The beach sand was not frozen during the morning and sand movement was not observed. Temperatures dropped in late morning; during the afternoon sand movement across the frozen

beach was observed. Deeper puddles of water on the beach served as sediment sinks for the moving sand until the puddles froze.

5. A winter squall on 25 February moved sand and snow inland. This event is described in more detail below.

The five strong wind events were responsible for a substantial portion of the winter sand movement.

Sediment movement took place at other times during the winter as well. In total, moving sand was observed on seventeen different days. Evidence of sand movement, such as dry-sand ripples and sand on snow, point to an additional eight days/nights on which sand movement occurred but was not directly observed. The sediment movement on 25 out of a possible 90 days indicates that cold-aeolian sand movement is not an isolated occurrence on the Presqu'ile Beach.

8.1.1.2 Patterns of Movement

The pattern of sand movement was generally from west to east--across the beach and onto the foredunes to the east--and blowing snow followed a similar pattern. A sudden squall on 25 February provided a dramatic example of characteristic snow and sand movement:

> At the time of the squall, samples of frozen sand were being extracted from the berm for water content determination. At 10:30 am snow began to fall under calm conditions (less than 1 m/s wind speed) and by 11:30 up to 2 cm of snow had collected on the beach surface. At 11:37 the wind abruptly increased to 6 m/s and blowing snow commenced immediately. Within five minutes some areas near the berm crest were cleared of snow and there was evidence of drifted snow and sand downwind. Within another five minutes the entire upwind slope of the berm was clear. By 12:07 pm evidence of windblown sand extended 25 metres downwind. By late afternoon the beach was largely clear of snow aside from some dense mixtures of snow and sand.

The events of 25 February demonstrate how quickly snow can be removed from the beach. The aeolian activity followed a pattern of movement that started upwind (near the icefoot) and worked its way downwind (towards the dunes). The pattern corresponds to the dominant wind direction over the beach. The net result of the recurring pattern of movement is deposition towards and on the foredunes (van Dijk 1993).

Only three instances of movement in the opposite direction--from east to west--were noted during the 1996-1997 field season. Sand moved from the beach to the lake on 12 December 1996 and from the beach to the icefoot on 12 and 13 March 1997. Long-term effects of this movement on the sediment budget are small; much larger amounts of sand are added to the beach from the bay each spring, summer and fall. In contrast, there are important short-term effects of the wind-blown sand on the icefoot. The change in surface albedo wrought by the darker sediment encourages melting, changes in icefoot shape, and may speed the spring breakup of the ice.

8.1.1.3 Uncommon Phenomena

An unusual feature of the 1996-1997 field season was the prolonged midwinter period of beach protection and aeolian inactivity. No aeolian movement took place from 25 January to 21 February, a period of nearly four weeks. During this time the beach remained entirely snow-covered except for fleeting patches of exposed sand on the berm. The period of beach protection followed the record January snowfalls measured in the area (Clark 1997). The snow cover was maintained by below-zero temperatures, low winds and frequent additions of snow. Although aeolian activity was prevented by the protective snow cover, the winds during this period were not strong enough to move exposed dry sand. The persistent snow cover and lengthy period of low winds were unusual on the Presqu'ile Beach in winter.

Another unusual feature of the recent winter was the late formation of the icefoot. Shore-fast ice did not form until 7 January 1997, at least seven days later than the usual ice formation between Christmas and New Years. The importance of the icefoot to beach protection was demonstrated in early January as winds were able to push water onto the beach where it froze. Approximately 180 m^2 of beach study area were protected from deflation during a concurrent sand-moving event. Much of the ice remained on the beach until milder temperatures on 22 January.

8.1.2 Erosion Pins

Frozen surface deflation was monitored at two beach plots of erosion pins. The sites, nicknamed "tower" and "midbeach" for their respective locations, were visited daily between 12 December 1996 and 14 March 1997. Pin heights above the ground were measured with a metre-stick when the beach sand was frozen and exposed. Accurate calculations of beach change require consecutive measurements of pin height above the frozen surface. Ice, snow, other precipitation, and beach thaws reduced the number of consecutive measurements to less than 10% of the measurement period (11 out of the 93 possibilities). Useable measurements were restricted to 19-21 December, 6-9 and 17-21 January, 3-4 and 12-13 (midbeach only) March. The ensuing discussion is further restricted by tainted data resulting from wind-blown detritus (6-9 and 17-21 January at the midbeach site), traces of snow (17-21 January at the tower site), poor lighting (3-4 March), and an observed midday thaw (12-13 March at the midbeach site).

8.1.2.1 Frozen Surface Deflation

Changes in erosion pin heights reflected erosion of sand by wind from the frozen surface. Table 8.2 shows ranges and averages of beach erosion (in mm) by site for specified winter periods. Data for each plot are obtained by calculating the change in height for each pin and determining the minimum, maximum, and average changes for the nine pins. The measured erosion is converted to equivalent weights of sand (table 8.3) using a conversion factor of 1.625 kg/m^2 for each mm of height. Results show that substantial amounts of sand were moved by wind during the December and January events.

One result of the erosion pin program that should not be overlooked is the small amount of data available for the final analysis. The data were limited by the variation in conditions at the sampling sites caused by precipitation (snow, sleet, rain) and periodic thawing of the surface. The repeated turnover in conditions was surprising, even given the variable winter weather to which the area is prone. In addition, the extended period of midwinter snowcover was unusual. Record snowfall also limited consecutive erosion pin measurements, and there were a significant number of warm-temperature periods.

			tower			midbeach	
dates	hours	min	max	avg	min	max	avg
19-20 December 1996	23	0	5	3	0	5	3
20-21 December 1996	25	3	4	3	1	5	3
6-7 January 1997	24	2	3	3	detritus and ice over site		
7-8 January 1997	22	1	4	3			
8-9 January 1997	24	0	3	2			
3-4 March 1997	22	0	2	1			
12-13 March 1997	24				2	7	3

Table 8.2 Mm/m^2 of sand eroded from frozen beach as indicated by erosion pins

			tower			midbeach	
dates	hours	min	max	avg	min	max	avg
19-20 December 1996	23	0	8.1	4.9	0	8.1	4.9
20-21 December 1996	25	4.9	6.5	4.9	1.6	8.1	4.9
total	48	6.5	13.0	9.8	3.2	13.0	8.1
/12-hours		1.6	3.2	2.4	0.8	3.2	2.0
6-7 January 1997	24	3.2	4.9	4.9	detritus and ice over site		
7-8 January 1997	22	1.6	6.5	4.9			
8-9 January 1997	24	0	4.9	3.2			
total	70	6.5	14.6	11.4			
/12-hours		1.1	2.5	2.0			
3-4 March 1997	22	0	3.2	1.6			
12-13 March 1997	24				3.2	11.4	4.9

Table 8.3 Kg/m^2 of sand eroded from frozen beach as indicated by erosion pins

8.1.2.2 Error in Erosion Pin Measurements

The accuracy of the erosion pin measurements is quite good. The unique characteristics of the cold environment reduce the errors to which erosion pin measurements are subject. There are seven main sources of data contamination according to Haigh (1977), and these sources are assessed with respect to the Presqu'ile measurements in table 8.4. The estimated accuracy of the erosion pin measurements is the accuracy of the measuring

Sources of data contamination (after Haigh 1977, 36, 43)	Application to Presqu'ile Beach erosion pin measurements in winter 1996-1997
1. disturbance during installation	offset by allowing surface to stabilize and freeze after installation
2. disturbance of erosion patterns by the pin	up to 1 mm of scour observed occasionally at base of pins; this scour did not affect measurements because width of metre-stick was appreciably greater than scour diameter
3. disturbance of pins caused by differences between the pin and the surrounding soil	i.e., frost heave in frozen ground; no evidence was expected or seen because sand-sized materials are not prone to heaving
4. trampling and vandalism	plots were roped off from surrounding area (but frozen ground could not be changed by people walking over it); no evidence of vandalism was observed and the ropes with corner stakes did not affect measurements
5. variation in the erosion pin's environment	measurements only made when the beach was frozen
6. disturbance during recording	not possible on frozen sand and measurements were not made when surface was thawed
7. errors in recording	±0.5 mm as a measurement error from the metre-stick

Table 8.4 Data contamination and Presqu'ile erosion pin measurements

device (metre-stick), or approximately ±0.5 mm. Assuming an error in time period of ±15 minutes in 24 hours, the deflation rates are accurate to 0.8 kg m^{-2} 12-$hours^{-1}$.

8.1.3 Sand Traps

Winter sand traps measured amounts and directions of sand moving over the frozen Presqu'ile Beach. Eight above-ground traps were placed on the beach on 27 occasions from 19 December 1996 to 13 March 1997. On three of the occasions, the traps caught snow without any sand and at one other time the traps remained empty. Twenty-three of the measurement periods, spanning 267.5 hours of winter activity, produced records of sand transport. The total of 45.1 kg of sand trapped over the winter corresponds to roughly 300 kg of sand moved per metre width.

Sand trap data were carefully screened to eliminate contamination by anomalous events. Wind speed and direction data were reviewed for each measurement period. Data were removed when the microclimate record indicated shifts in wind direction but no sand was captured in the corresponding sand trap. Abrupt drops in wind speed to less than 3 m/s often accompanied the shifts in wind direction and had significant effects on sand movement. These data were also removed from subsequent analysis and the measurement period lengths were adjusted accordingly. Nine of the 23 measurement periods were affected by the screening process and 62 hours of microclimate data were eliminated from further analysis. The remaining data on wind speed, direction, microclimate and durations better described the sand movement recorded at the sand traps.

8.1.3.1 Direction of Movement

Sand trap measurements show a distinct pattern of cold-aeolian transport by direction (figure 8.1). Each suite of measurements included traps oriented in the eight directions. The graphed results have a distinct peak from 270 to 315 degrees from north. The dominance of transport from the W and NW is in good agreement with the dominant wind direction on the Presqu'ile Beach in winter.

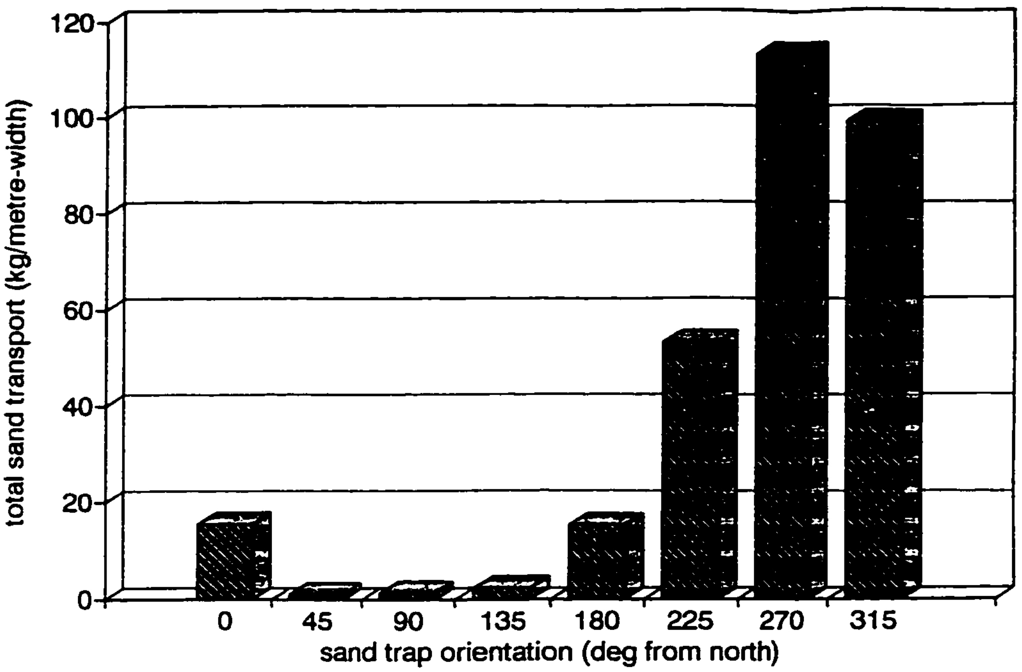


Figure 8.1 Trapped sand (by direction) on Presqu'ile Beach from December 1996 through March 1997

8.1.3.2 Rates of Transport

The sand trap data are converted to transport rates to permit comparison between measurements. Field sampling periods varied in length depending on how quickly the sand traps filled, whether the traps were left out overnight, transportation constraints, and other beach activities. Quantities of trapped sand for the different periods are converted to standard units with the equation

$$q=\frac{trapped\ sand\,(kg)}{trap\ width\,(m)\cdot time\,(sec)} \qquad (8.1)$$

where q is sand transport expressed as kg of sand per m-width per second. Table 8.5 gives the total transport and transport rate for the dominant direction of movement--the direction in which the greatest amount of sand was trapped--in each period. Transport rates range from 1.8 x 10^{-6} kg m-width^{-1} sec^{-1} to 8.9 x 10^{-4} kg m-width^{-1} sec^{-1}.

date	minutes	direction	measured transport g/0.15-m	transport rate kg/m/sec	1-m wind speed	
					avg	max
19 Dec	295	W	2351	8.9E-04	6.26	8.64
19-20 Dec	985	W (NW)	5872	6.6E-04	6.52	8.90
20 Dec	240	NW (W)	1393	6.4E-04	8.33	11.25
20 Dec	240	W	1657	7.7E-04	6.83	10.40
20-21 Dec	1070	W	1153	1.2E-04	5.53	7.83
21 Dec	350	SW	1059	3.4E-04	6.77	9.29
8-9 Jan	620	NW	54	9.7E-06	4.73	7.23
15 Jan	240	W (S)	18	8.2E-06	4.93	7.31
17 Jan	420	NW	968	2.6E-04	7.82	12.03
17-18 Jan	450	W	21	5.1E-06	8.75	13.12
18 Jan	460	W	370	8.9E-05	2.52	4.51
18-19 Jan	975	W (NW)	571	6.5E-05	5.18	7.45
19-20 Jan	1260	W	517	4.6E-05	8.53	12.21
20 Jan	315	W	91	3.2E-05	8.35	11.95
24 Jan	450	SE	171	4.2E-05	n.a.	n.a.
22-23 Feb	555	NW	1109	2.2E-04	5.50	8.39
24 Feb	720	N	588	9.1E-05	6.74	10.07
24-25 Feb	75	NW	17	2.6E-05	5.46	8.11
25 Feb	435	W	142	3.6E-05	7.45	10.83
25-26 Feb	720	W (SW)	767	1.2E-04	8.10	11.99
3-4 Mar	720	E	12	1.8E-06	2.45	5.18
12 Mar	390	NW	31	8.8E-06	5.89	8.99
12-13 Mar	225	NW	8	3.8E-06	4.35	6.85

Table 8.5 Summary of sand trap results and rates of transport on Presqu'ile Beach

Examination of the data indicates very little correlation between transport rates and measured wind speeds. Average, maximum, and cubed wind speeds were compared to transport rates and total transport with very low correlations seen in any of the comparisons. Average wind speeds are plotted against transport rates in figure 8.2 as an example of the widely scattered data.

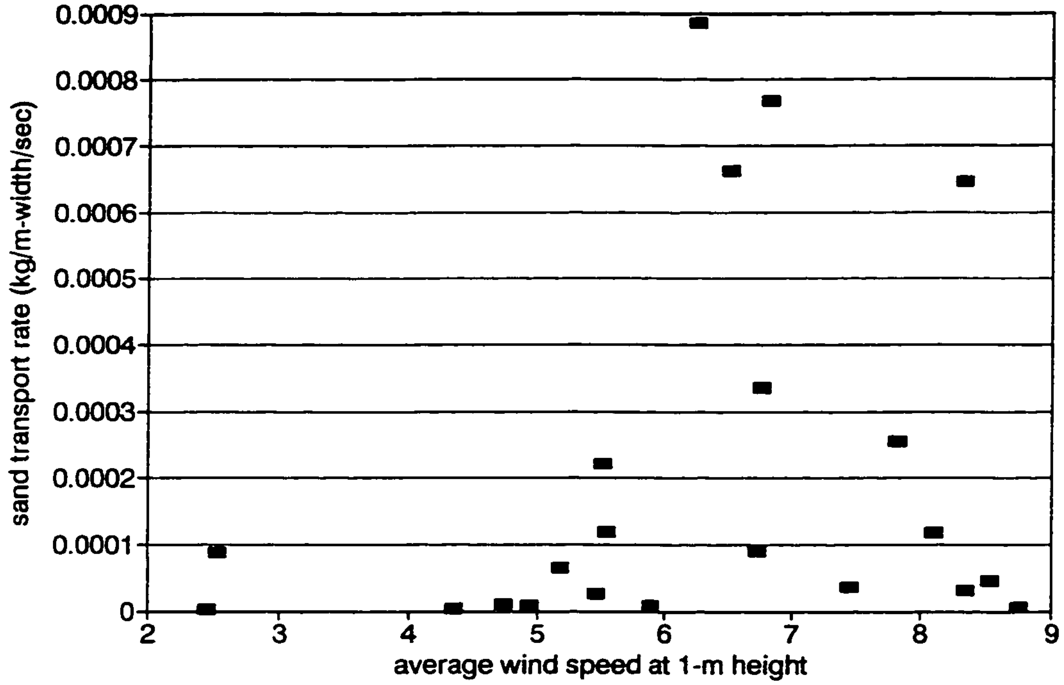


Figure 8.2 Wind speeds vs. transport rates for Presqu'ile Beach

The absence of relationship between wind speed and transport rate is unusual in an aeolian process. The low transport rates at high wind speeds are especially unexpected in traditional geomorphology. These odd results can be explained by the singular nature of the cold environment. Supply limitations posed by the interstitial ice in the frozen ground control the erosion of sand and its transport across the beach. Strong winds are therefore carrying considerably less sediment than they could hold if the supply was not limited.

8.1.3.3 Source Areas for Sediment

The area supplying the moving sediment is important in the light of surface constraints on cold-aeolian processes. The maximum fetch from which sand is supplied to each trap varies according to trap direction (figure 8.3). The winter environment is often complex with snow, ice and other factors reducing the areas of exposed sand. Effective fetches have been calculated for each measurement period based on the direction of movement

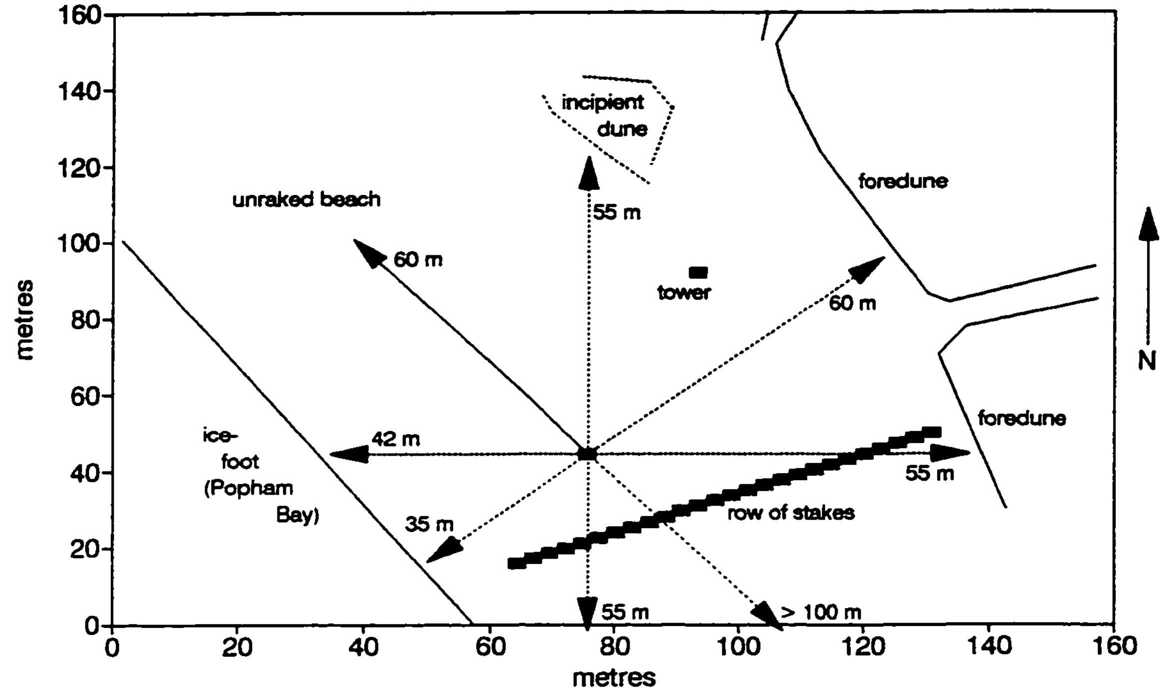


Figure 8.3 Maximum fetch in sand trap directions

and records of beach cover for the same time (table 8.6). Estimated accuracy of the effective fetches is ±20% because beach cover was visually assessed perpendicular to the shoreline and then converted to distances in the appropriate direction. The effective fetches represent source areas for sediments moving past and into the sand traps located in the midbeach area.

A comparison of effective fetches with rates of transport indicates that sand movement increases as the length of the source area increases. Regression analysis found a moderate correlation between the transport rate and effective fetch. This result is especially significant in view of the large possible error in fetch estimates and the negligible correlation between transport rate and wind speed. In the context of cold-aeolian processes, the source area for sediment supply is more important to transport rate than wind speeds over the surface.

date	surface description in fetch direction	metres exposed (perp.)	direction of sandtrap	fetch in trap direction	direction of wind	fetch in wind direction
19 Dec	completely exposed	35	270	44	274	47
19-20 Dec	completely exposed	35	270	44	288	63
20 Dec	completely exposed	35	315	60	281	53
20 Dec	completely exposed	35	270	44	287	61
20-21 Dec	completely exposed	35	270	44	283	56
21 Dec	completely exposed	35	225	35	218	36
8-9 Jan	3 m + midbeach	3	315	25	302	18
15 Jan	berm +; midbeach	12	270	15	225	12
17 Jan	berm +; midbeach	3	315	25	284	19
17-18 Jan	berm +; midbeach	12	270	15	284	19
18 Jan	berm +; midbeach	12	270	15	216	12
18-19 Jan	berm +; midbeach	12	270	15	289	22
19-20 Jan	berm +; midbeach	12	270	15	261	14
20 Jan	berm +; midbeach	15	270	19	273	20
24 Jan	midbeach; by dunes		135	90	n.a.	n.a
22-23 Feb	berm +; midbeach	16	315	30	306	58
24 Feb	berm +; midbeach	6	0	5	308	25
24-25 Feb	berm +; midbeach	6	315	30	300	16
25 Feb	berm +; midbeach	12	270	15	232	12
25-26 Feb	berm +; midbeach	13	270	16	246	13
3-4 Mar	exp. towards dunes	27	90	27	62	27
12 Mar	berm +; midbeach	3	315	25	303	37
12-13 Mar	berm +; midbeach	3	315	25	309	53

Table 8.6 Effective fetches for Presqu'ile sand movement in direction of dominant sand trap and measured wind direction (metres exposed indicates the length of exposed sand perpendicular to the shoreline)

8.1.3.4 Frozen Surface Deflation

Transport rates and effective fetch measurements are used to generate deflation rates for the sediment supply area. The deflation rate calculation assumes that the sand traps are capturing a representative portion of deflated material as it moves across the beach. Fetch and transport rate are combined in the following equation:

$$\mathit{deflation\ rate} = \frac{q \cdot 43200(\mathrm{sec})}{\mathit{effective\ fetch}(m)} \tag{8.2}$$

where the deflation rate has the units kg m-width^{-2} 12-hour^{-1}. Calculations indicate Presqu'ile Beach deflation rates of 0.01 to 0.86 kg m-width^{-2} 12-hour^{-1} (table 8.7).

date	transport rate kg/m-width/sec	effective fetch in metres	deflation rate kg/sq metre /12-hours
19 Dec	8.9E-04	44	0.86
19-20 Dec	6.6E-04	44	0.64
20 Dec	6.4E-04	60	0.46
20 Dec	7.7E-04	44	0.75
20-21 Dec	1.2E-04	44	0.12
21 Dec	3.4E-04	35	0.41
8-9 Jan	9.7E-06	25	0.02
15 Jan	8.2E-06	15	0.02
17 Jan	2.6E-04	25	0.45
17-18 Jan	5.1E-06	15	0.01
18 Jan	8.9E-05	15	0.25
18-19 Jan	6.5E-05	15	0.18
19-20 Jan	4.6E-05	15	0.13
20 Jan	3.2E-05	19	0.07
24 Jan	4.2E-05	90	0.02
22-23 Feb	2.2E-04	30	0.32
24 Feb	9.1E-05	5	0.78
24-25 Feb	2.6E-05	30	0.04
25 Feb	3.6E-05	15	0.10
25-26 Feb	1.2E-04	16	0.31
3-4 Mar	1.8E-06	27	0.00
12 Mar	8.8E-06	25	0.02
12-13 Mar	3.8E-06	25	0.01

Table 8.7 Deflation rates for Presqu'ile Beach calculated from transport rates measured at sand traps and effective fetches in dominant trap direction

Concurrent sand trap and erosion pin measurements allow estimates of beach deflation to be compared. The largest overlap of measurements is from 19-21 December. When sand trap results are adjusted to cover the same 48 hours as erosion pin measurements, sand traps indicate 1.9 kg/m^2 were deflated from the frozen surface. Average deflation at the midbeach erosion pin site was 8.1 ± 3.2 kg/m^2 during the same period. Sand trap data appear to underestimate deflation by approximately 4 times.

8.1.3.5 Error in Sand Trap Measurements and Analysis

The comparison of beach deflation indicates discrepancies between erosion pin and sand trap measurements. Erosion pin error has already been discussed and does not account for the large difference between the results. Error analysis of sand trap data point to multiple sources of uncertainty. The error grows as the original data (amounts of trapped sand) are manipulated to produce rates of sand transport and deflation. Six sources of error are described below.

Error inherent to sand traps. Measurements from vertical sand traps, that is, traps which extend into the air stream, can only be approximate because the presence of the collecting device interferes with the air stream (Goudie 1981, 325). Vertical traps disturb the wind flow pattern and can lead to local scour at the base of the trap. As a result, a portion of the moving sand goes around the trap instead of entering it. Vertical trap efficiencies (ratios of trapped sand to moving sand) as low as 20% have been recorded (Horikawa and Shen 1960). Sherman and Hotta (1990) recommend cylindrical traps, such as the Leatherman sampler, as an excellent alternative to more expensive designs. An early version of the winter sand trap demonstrated better efficiency at high transport rates than the Leatherman sampler (Grant 1992, 44). In the absence of direct testing of winter sand trap efficiency, it is important to remember that the trap may underestimate sand movement by significant amounts.

Error associated with winter sand traps as they fill. The efficiency of a winter sand trap decreases as the trap fills. The trap design includes a fine mesh liner which allows wind to pass through but captures moving grains. Wind flow through the trap is affected as sand piles up in the liner. Large amounts of collected sand may interfere with further collection by stretching the liner and permitting grains to pass through the mesh.

Error associated with time period. The long and varied measurement periods produce two types of error. Sand movement may not be uniform throughout the test period and episodes of inactivity decrease the final estimates of transport rates. Measurement error is also associated with time; the accuracy of recorded time is ±15 minutes to account for removing the samples, resetting the traps, and so on.

Error associated with fetch and effective fetch. The large errors involved in fetch calculations have already been discussed. Additional sources of error include the $\pm 5^{\circ}$ leeway for wind direction measurements and the uncertainty inherent to averaging wind directions when infrequent sand movement occurs. Fetch accuracy influences calculations of deflation from the frozen beach. Fetch estimates which are too small will overpredict deflation rates and vice versa.

Inhomogeneity of upwind surfaces. Effective fetch estimates merely record the amount of upwind beach area that is exposed and make no other allowances for surface inhomogeneities such as snow and ice. Thus, discontinuous exposed areas extending along the maximum fetch are deemed equivalent to a continuous shorter fetch near the sand trap location. Discontinuities of snow, ice or open water between the sediment source and the sand traps may become an area for sediment deposition and absorbs moving sand before it can reach the sand traps. All three of these scenarios were observed over the course of the winter, and the corresponding sand trap analysis underestimates the amount of sediment released from distant upwind sources.

Snow and blowing snow during part or all of measurement period. Snow and blowing snow complicate measurements of sand movement over the frozen beach. Snowfall during a measurement period temporarily protects the beach, and a portion of the wind energy is directed to moving the snow instead of sediments. Sand traps contained mixtures of snow and sand on 10 of the 23 test periods, and snow was the predominant trapped material on 7 of these occasions.

The aforementioned errors and influences can combine to produce sand trap measurements which significantly underestimate sand movement over the frozen beach. The uncertainty in measurement increases as field conditions become more complex. Erosion pin results under relatively simple conditions (little snowfall, no beach protection by snow or ice) suggest that sand trap efficiency in estimating deflation may be on the order of 25%.

The deliberate evaluation of error is not intended to discount the usefulness of sand trap results. Instead, sources of error are presented to provide a fair estimate of measurement accuracy. Identifying the error is an important step towards better measurements and improved study design in the future. Two important aspects of the current results put the sand trap error into perspective.

The Presqu'ile sand trap data are among the first direct quantitative field measurements of cold-aeolian sediment movement. New research techniques and environmental constraints are expected to produce uncertainty at this stage of data-collection. Nevertheless, the sand trap results provide solid evidence that significant amounts of material are eroded from frozen sand under sub-zero temperatures.

The sand movement is substantial given the complexities of the cold-environment. Results point to a net movement of 33 kg per 0.15 m-width moving across the beach from 278° (figure 8.4). This amount is equivalent to 220 kg/m-width over the course of the winter, or 13 200 kg for the 60-metre long study area. The error analysis highlights the probability that actual sand movement is greater than the movement measured by the sand traps. Taken as a minimum, the sand trap data represent a significant input of sand to the Presqu'ile backbeach and foredune area.

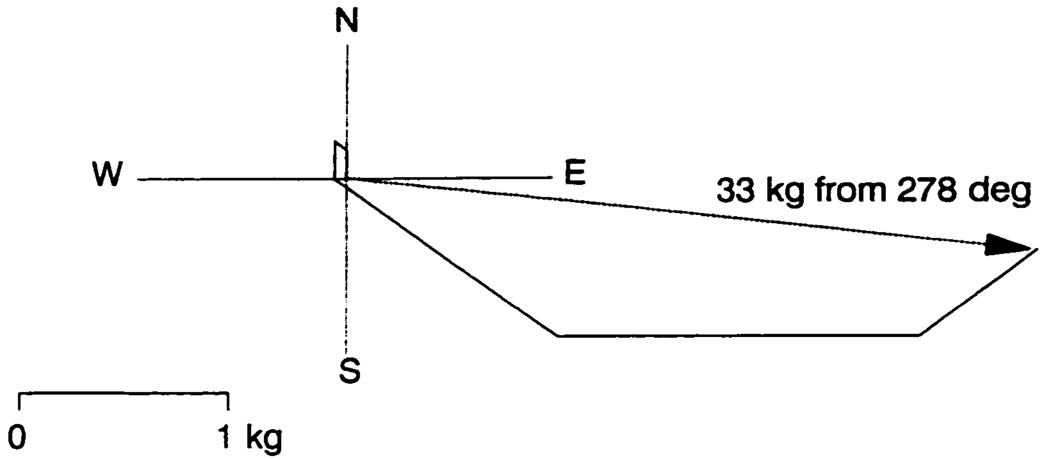


Figure 8.4 Net sand transport across Presqu'ile Beach by weight and direction (per 0.15-metre width as measured by sand traps)

8.2 Field Measurements as Model Inputs

The computer model COLDAEOL.BAS requires inputs of microclimate data and surface conditions to make predictions of sand release and transport. Microclimate inputs for the model are derived from the data collected at the beach microclimate site. Field measurements provide the necessary information on snow, ice and surface water content.

8.2.1 Daily Observations: Snow and Ice

Daily beach observations provide the inputs of snow and ice cover required by the cold-aeolian model. The continuous winter record shows whether the beach was covered by ice and/or snow or was exposed to aeolian processes. Beach cover varied by location and a decision was made to use a portion of the berm near the icefoot in testing the model. This location was the most quickly and frequently exposed after snow-cover and was rarely covered by ice. Values of 0 (no cover) and 1 (cover) are assigned to snow and ice cover for this area as model inputs. Ice cover was extremely rare in this location and snow cover was usually brief with the exception of the three-week period from late January to mid February.

8.2.2 Surface Water Content

Periodic sampling of the beach surface provided the surface water content data required by the cold-aeolian model. Sediment samples were taken from the surface when there was a thin and removable frozen layer, when the surface experienced shallow thawing, and with an impact-driven soil sampler when the beach was frozen. Data collection took .place on eight days for a total of 128 samples. The distribution of exposed frozen sand determined sampling sites. When possible, samples were taken across the width of the beach using the wooden stakes as benchmarks. When a more restricted section of the beach was exposed--usually the berm, a number of samples were taken from random locations or from short transects across the exposed area. Water content was found by oven-drying the sediment samples.

Sample analysis showed high water contents in the frozen beach for most of the winter (figure 8.5). Water contents ranged from 11% to 35% by weight (with one additional low value of 6%). The averages between 20% and 30% indicate that the frozen surface contains a lot of frozen water. In laboratory reconstruction of samples, oversaturation occurred at roughly 23% when sand would settle out and ice would form on the surface of test blocks as they froze. Forty-seven percent of the field samples had water contents above this level, and a full eighty-four percent had water contents above 20%.

The high water contents appear to be characteristic of the Presqu'ile Beach surface in winter. Occasional thawing and refreezing of the surface may provide an explanation for the extreme values. Water from snow and ice is unable to drain through the underlying frozen layer and may refreeze into an oversaturated top layer. Despite the high water contents, samples were visually homogenous with no evidence of ice segregation or features. Under the classification system of chapter five, the ground was very strongly

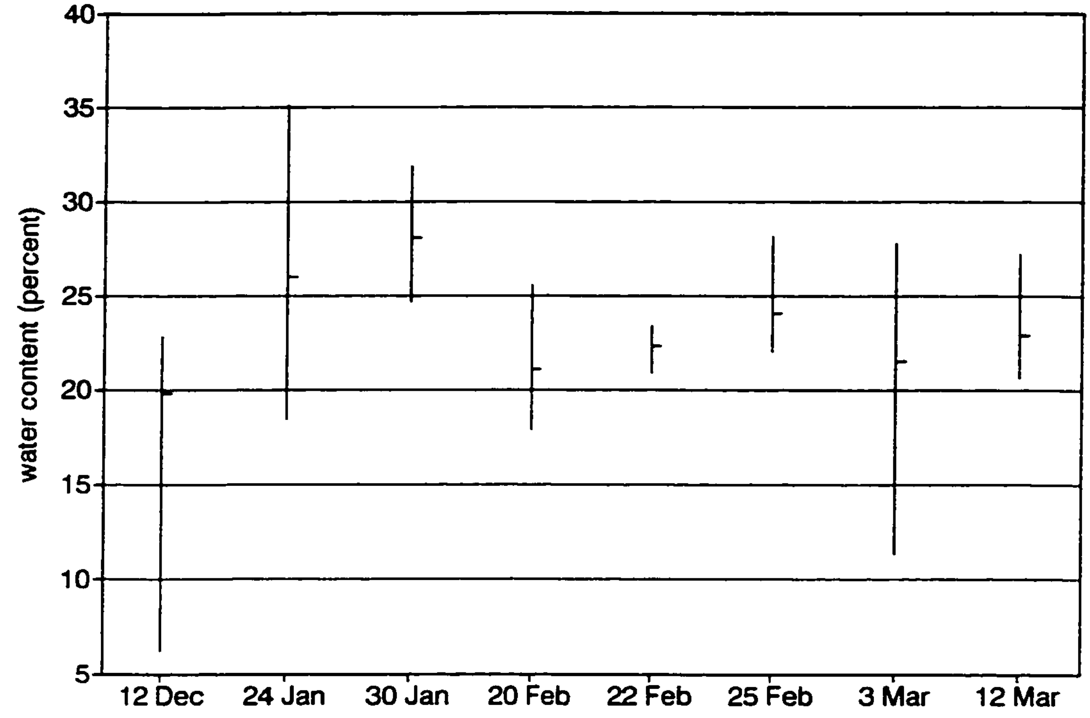


Figure 8.5 Water content of Presqu'ile Beach during winter 1996-1997

cemented with no possibility of the wind physically detaching sand grains from the surface.

A water content of 23% was used as the model input for the entire winter. The input is the average water content for the entire measurement period instead of the individual daily averages. Values above 23% represent oversaturated frozen sand and lie outside the bounds of the measurements used to develop the model. Individual averages which were below 23% were not inserted into the model because frequent precipitation (rain, freezing rain, snow) and melting added water to the beach surface between sampling times.

8.3 Comparison of Predicted Movement with Measured Movement

Predictions made by the computer model are compared to erosion pin and sand trap measurements. Two input files, corresponding to the time periods of the erosion pin and sand trap measurements, were created and fed into the computer model. Each input file used microclimate data from at the beach site and water contents of 23%. Input values for ice and snow were forced to 0 (i.e, not present) for comparison purposes. Positive indications of snow would produce outputs of 'no movement' during periods when movement was observed. COLDAEOL.BAS used the input files to generate two output files which contained predictions of sand release, sand movement, and indications that melting may have occurred during some of the test periods.

8.3.1 The Model and Erosion Pin Measurements

Model predictions compare favourably to erosion pin measurements of deflation (table 8.8). Predictions of released sand lie well within the ranges of erosion pin measurements for all but the period on 3-4 March when the predicted amount is high. With a 6 m/s threshold for movement, the model indicates that no sand moved during the final four test periods. These predictions were not borne out by the erosion pin measurements nor by recorded observations of sand movement during each of those periods.

dates	hours	tower kg m^{-2} 12-hrs^{-1}	midbeach kg m^{-2} 12-hrs^{-1}	model L	model Q
19-20 December	23	0 - 8.1 (4.9)	0 - 8.1 (4.9)	3.64	3.64
20-21 December	25	4.9 - 6.5 (4.9)	1.6 - 8.1 (4.9)	3.65	3.65
total	48	6.5 - 13.0 (9.8)	3.2 - 13.0 (8.1)	7.29	7.29
6-7 January	24	3.2 - 4.9 (4.9)	---	3.46	3.46
7-8 January	22	1.6 - 6.5 (4.9)	---	3.01	0
8-9 January	24	0 - 4.9 (3.2)	---	3.32	0
total	70	6.5-14.6 (11.4)	---	9.79	3.46
3-4 March	22	0 - 3.2 (1.6)	---	3.74	0
12-13 March	24	---	3.2 - 11.4 (4.9)	3.96	0

Table 8.8 Deflation at erosion pins and model predictions of released (L) and deflated (Q) sand

8.3.2 The Model and Sand Trap Measurements

Model predictions of released sand are high compared to measurements made with sand traps (figure 8.6a). There is better agreement between the results when predictions of moving sand are used (figure 8.6b). The best agreement occurs near the beginning of the measurement period--using the measurements made in December 1996.

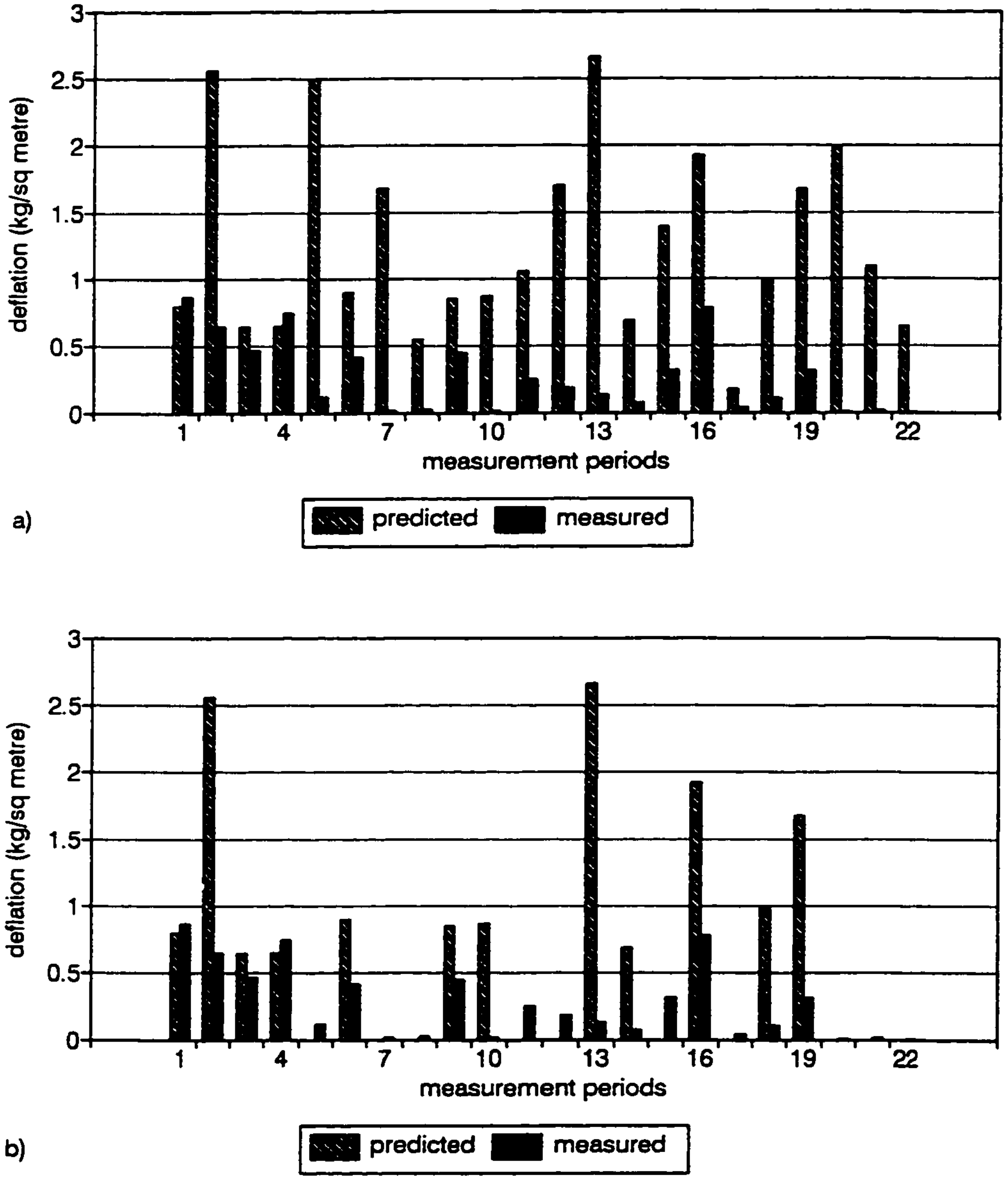


Figure 8.6 Measured transport rates compared to a) predicted sand release and b) predicted sand movement

Many of the reasons for differences between model and sand trap results are found in the discussion of error associated with the sand trap measurements. Specific circumstances for test periods are summarized in table 8.9. The reasonable agreement between model and field measurements near the beginning of the field season correspond to a time when the frozen beach was fully exposed with no ice cover. As the season progressed, the beach surface became more complex with additions of ice and snow. Sand movement itself became more complex and mixtures of snow and sand were captured by the sand traps on 10 of the 23 occasions.

#	date	deflation difference	extenuating factors
1	19 Dec	-0.06	
2	19-20 Dec	1.92	overnight--sand traps overflowing
3	20 Dec	0.18	
4	20 Dec	-0.10	
5	20-21 Dec	2.38	overnight snowfall; blowing snow
6	21 Dec	0.49	
7	8-9 Jan	1.66	intervening (smooth) ice; infrequent movement
8	15 Jan	0.53	variability of exposed area; intervening ice
9	17 Jan	0.40	intervening rough ice has trapped sand; snow squalls
10	17-18 Jan	0.86	blowing snow
11	18 Jan	0.81	
12	18-19 Jan	1.52	
13	19-20 Jan	2.53	more snow overnight; evidence of freezing rain
14	20 Jan	0.62	
15	22-23 Feb	1.07	intervening ice with open water just before sand traps
16	24 Feb	1.14	intervening ice covered with snow has evidence of
17	24-25 Feb	0.13	deposited sand
18	25 Feb	0.88	midday snowfall; variable fetch as snow blows inland
19	25-26 Feb	1.36	
20	3-4 Mar	1.98	intervening ice; infrequent movement
21	12 Mar	1.07	intervening (rough) ice; infrequent movement
22	12-13 Mar	0.63	

Table 8.9 Differences between predicted and measured deflation and measurement circumstances

8.3.3 Assessment of Model

The comparison of model predictions with field measurements is inconclusive. Model predictions lie well within the range of erosion pin results but the sample size is small. Sand trap measurements suggest that the model overpredicts sand release and movement but error analysis suggests that sand traps underestimate beach deflation. Sand trap results and model predictions lie roughly within the same order of magnitude and are even quite close near the beginning of the field season when extenuating circumstances are minimized.

The comparison between measured and predicted deflation did reveal a tendency for the model to underpredict occurrences of sand movement. On occasion, the erosion pin and sand trap data contradicted model forecasts that no sand was moving over the surface. This discrepancy could be adjusted by choosing a lower threshold for movement in the model.

Model results suggest a cautious optimism and a program of continued testing. Optimism is recommended because of the agreement between model predictions and measurements (both erosion pin and sand trap) in mid-December 1996. Discrepancies during the rest of the field season can be explained in terms of measurement error and environmental complications. Much more testing is required to confirm the present results and produce better field measures of sand movement. Future testing can also be used to expand the range of conditions over which the model holds true.

The most effective method for future testing may be an expanded erosion pin program. The pins produce a direct measure of surface deflation which can be compared to model predictions. Uncertainty in erosion pin results is also well-defined. The greatest difficulty with the erosion pin measurements has been obtaining sufficient data. Shorter measurement periods are unacceptable because they bring the error into the same range as the measurements themselves. Cooperative weather in future winters would be beneficial to the measurement program.

Sand trap testing should be continued with improvements made to test accuracy. Some errors could be reduced by using shorter sampling times (1- to 2- hour periods during heavy movement) and by making more precise measurements of fetch and beach conditions. Errors could be further defined by testing sand trap efficiency in a wind tunnel and perhaps by making minor adjustments to trap design.

Model predictions can also be improved by more field measurements of water content and sand movement. Water content determination of frozen sand has been made possible with the introduction of the impact-driven soil sampler. Measurements are suggested near the erosion pin site and in the sediment source area when erosion pin and sand trap measurements are being made. Results would indicate whether the high water contents of this study are representative of most sites and times during the winter. Additional observations of sand movement are needed to confirm the threshold of movement to be used in the model.

8.4 Summary

Field measurements at Presqu'ile Beach have made quantitative assessments of cold-aeolian sand movement under a range of winter conditions. Measurements at erosion pins indicate that up to 8 mm of sand could be deflated from the surface in a 24 hour period. Sand trap results demonstrate that at least 220 kg of sand per m-width moved across the beach over the course of the winter. Patterns of movement were predominantly from west to east. Snow and ice protected portions of the beach for varying lengths of time during the winter. Aeolian erosion most often took place from exposed sand near the lake edge and deposition occurred toward the back of the beach and over the foredunes.

Model testing against field measurements indicate that predictions agree with erosion pin measurements but overpredict sand release and movement compared to sand trap measurements. More testing is recommended in light of the small dataset for erosion pins and the large errors associated with the new winter sand traps.

Chapter Nine

COLD-AEOLIAN ACTIVITY IN CONTEXT

The Walrus and the Carpenter were walking hand in hand:
They wept like anything to see such quantities of sand.
"If only this were cleared away," they said, "it would be grand!"
Lewis Carrol

Cold-aeolian processes take place under specific microclimate and surface conditions. Phenomena and conditions fit into larger spatial, temporal and theoretical contexts. The objective of this chapter is to explore different contexts for cold-aeolian activity. At a local scale, the place of sediment movement by wind in the Presqu'ile winter is examined. Expanding the temporal scale prompts questions about the importance of winter processes in annual and long-term changes to the beach/dune complex. But the study results are not limited to the Presqu'ile area. Quantities of sediment movement can be compared to observations by researchers in various cold regions. The study results also fit into a broader context of geomorphological research.

9.1 Winter at Presqu'ile

The Presqu'ile winter is characterized by variability. Temperatures easily drop 10 or 20 degrees Celsius in the space of a few hours, often passing through the freezing point on the way. Most forms of precipitation are possible: rain, ice pellets, snow, and various other forms of frozen water. The wind regime ranges from periods of dead calm to winds so intense that outdoor activities are difficult. In response to the variations in weather, landscape features and appearance change often during the winter. The cold-aeolian activity which occurs under specific combinations of weather and surface cover is both affected by existing ground variations and itself an agent of topographic change.

Winter is described as the cold season between autumn and spring in the northern latitudes. Strictly defined, the season extends from the winter solstice to the vernal equinox. In the study area, temperatures dip below zero earlier in December and noticeable warming occurs by the middle of March. The nominal winter period for this study extends from 15 December through 15 March. These boundaries are used with the understanding that cold temperatures are not limited to this period.

9.1.2 Warm Temperatures

Non-freezing conditions exist on the Presqu'ile Beach for a significant portion of the winter. Data from five recent winters indicate that air temperatures are above freezing for approximately 25% (± 10%) of the time, with most warm temperatures between 0°C and 8°C (table 9.1). The number of days in which temperatures exceed 0°C is even higher, ranging from 36 to 56 percent of the winter. Temperature variations across the freezing mark produce many opportunities for freezing and thawing at the beach surface. The warmer temperatures are not limited to the start and end of the winter but occur at any time. A typical winter pattern oscillates between warm and cold temperatures with

	1992-1993	1993-1994	1994-1995	1995-1996	1996-1997
average temp.	-5.3	-8.2	-3.7	-6.2	-4.1
minimum temp.	-25.5	-30.5	-25.2	-25.2	-25.1
maximum temp.	7.2	8.0	12.2	8.5	8.1
days in which temperature rose above zero	47	34	51	32	50
temperature ranges (deg C)	% frequencies				
-30 to -25	0.0	2.6	0.1	0.0	0.0
-25 to -20	1.7	10.9	1.6	2.2	1.0
-20 to -15	6.0	17.0	4.4	8.6	6.7
-15 to -10	16.2	19.5	11.8	18.8	13.9
-10 to -5	23.2	15.9	19.4	24.7	23.4
-5 to 0	28.0	17.8	27.1	23.1	30.5
0 to 5	23.9	15.9	31.2	20.9	22.7
5 to 10	1.0	0.5	3.7	1.8	1.9
10 to 15	0.0	0.0	0.6	0.0	0.0
# of half-hours	4365	4368	4367	4320	4315

Table 9.1 Temperature summary for Presqu'ile winters in °C, 1992-1997

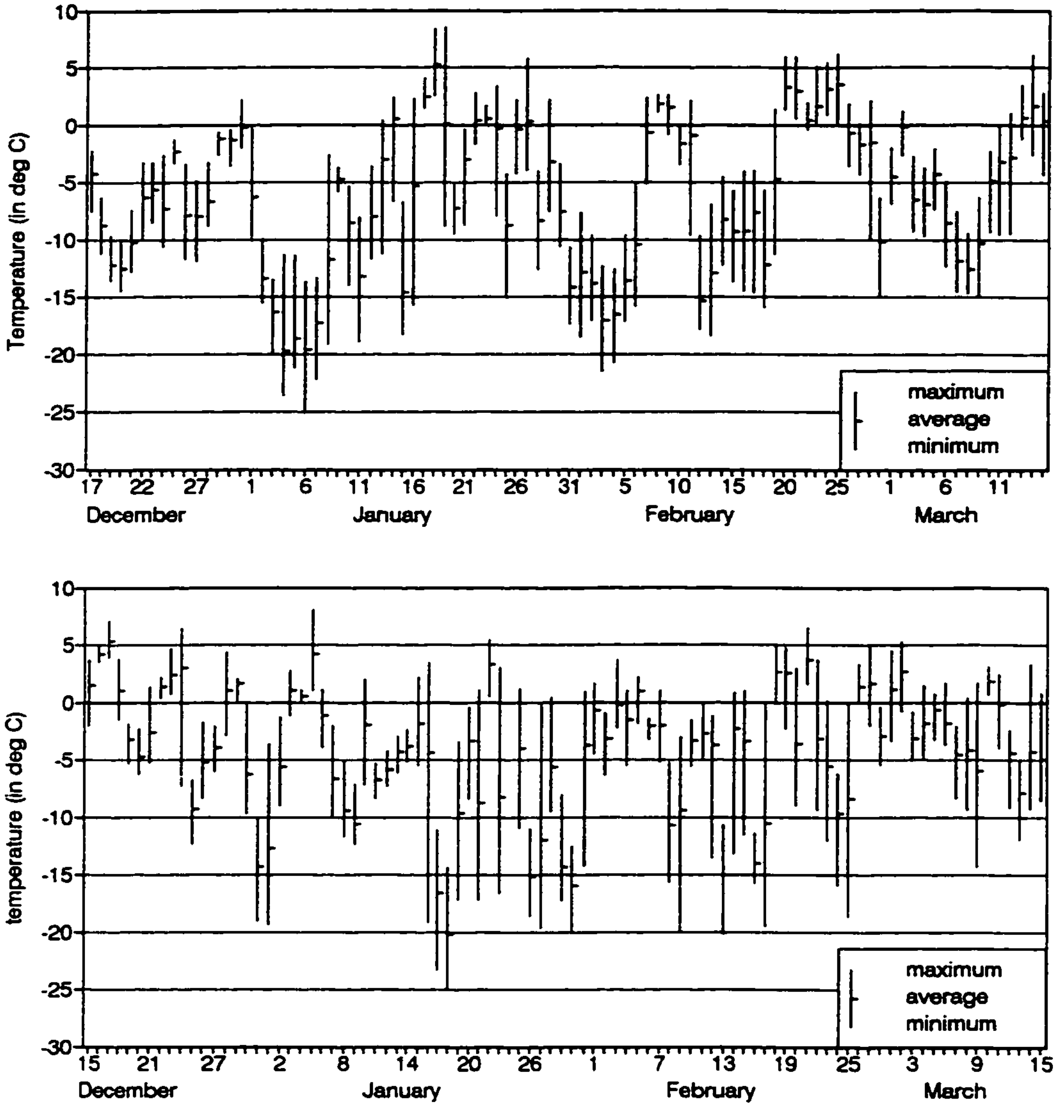


Figure 9.1 Daily temperatures for Presqu'ile Beach during a) 17 December 1995 through 15 March 1996 and b) 15 December 1996 through 15 March 1997

variations in the amplitude and frequency of the oscillations. Temperature graphs (figure 9.1) show the differences between the distinctive oscillations of 1995-1996 and the more frequent changes of 1996-1997. The rapid changes of the latter winter give the beach little time to stabilize at a prevailing temperature.

Warm winter periods are times when water is redistributed across beach and dune surfaces. Snow-melt, ice-melt, rainfall, and the thawing of frozen ground produce liquid water at the surface. Although sand is usually well-drained, an underlying frozen layer prevents the water from infiltrating the ground. Instead the water becomes runoff or pools at the surface where it can evaporate. Rills and gullies are common in the thawed layer when temperatures remain warm for several days. Slumping and failure occur on oversteepened dune slopes as saturated sand slides down over the frozen layer. Slope failure mostly takes place during spring; midwinter thaws are too short to melt the deep snow-drifts which accumulate behind the dunes. Slope failure is less common on drier windward slopes.

Very little aeolian activity takes place during warm winter intervals. Sand movement has rarely been observed when surface sediments are thawed during the winter months. The aeolian movement is inhibited by the plentiful surface water. Meltwater pooling in beach depressions shelters the underlying sand from wind action. Thawing sand in higher areas of the beach tend to be saturated or oversaturated. Thawing can even moisten previously dried sand as excess water moves to fill available pore spaces. Despite warmer temperatures, drying occurs slowly as water released from the frozen layer at depth moves towards the drier surface sand.

9.1.2 Precipitation

The Presqu'ile area receives large amounts of precipitation from December through March (table 9.2). The precipitation falls mainly in the form of rain and snow, although freezing rain, sleet, and ice pellets are a few of the other precipitation types possible in the area. Data for the area show that precipitation amounts are fairly evenly divided between rain and snow for all the winter months. On average, precipitation is recorded on nearly one out of every two days.

Precipitation protects beach and dune surfaces. Snowfall and refrozen rain or meltwater shelter sediments from wind and water erosion. The ground distribution of snow and/or

	December	January	February	March
rain				
average in mm	57.9	31.8	33.7	54.6
average number of days	7	4	4	6
days in 1996/1997	5*	5	8	5*
snow				
average in cm	48.8	49.0	35.1	28.3
average number of days	10	12	9	6
days in 1996/1997	5*	14	10	6*
precipitation				
average in mm	106.9	80.8	68.8	82.0
average number of days	14	14	11	11
days in 1996/1997	10*	17	16	10*

Table 9.2 Precipitation in the Presqu'ile area, December through March from thirty-year climate normals for Smithfield CDA station (Environment Canada, 1993: 100) and beach observations; * indicates 15-31 December or 1-15 March

ice encourages preferential erosion of unprotected areas. Snow is most often found in backbeach drifts and to the lee of dunes where it is deposited during redistribution by wind. Ice forms in shallow depressions where water collects during warm periods. It is not unusual for the entire beach to be protected by snow or by ice resulting from freezing rain. Complete protection rarely stays for long in the active coastal environment.

Precipitation contributes to slowing down the erosion of frozen exposed surfaces. Rain- and melt- water cannot drain through the frozen sand underlying the thawed layer. Instead the water fills the pore spaces of unfrozen sand at the surface. The water freezes in place when temperatures drop below zero and frozen sediments with high water contents are formed. Resistance to movement depends on the water content; sediments become more resistant to erosion as their water contents increase.

Rain, snow, and the eventual meltwater are directly responsible for erosion on very small scales. Heavy rainfall on thawed sediments produces rain-splash and other tiny erosion features. Rain and meltwater moving over and through thawed sediments during warm periods produce small drainage features such as rills. Precipitation also supplies the water which contributes to slope failure where saturated thawed sediments are present on steepened slopes.

9.1.3 Coastal Ice

Coastal ice accumulates along the Presqu'ile Beach shoreline during winter months. The shore-fast ice prevents sediment erosion and deposition along the beach edge by wave action. As a result, sediments which are deflated from the Presqu'ile beach are not replaced until wave action resumes in the spring when the ice disappears. The ice itself moves sediments within a narrow zone at the beach edge of the ice foot. In extreme cases, ice-push flings sediments and ice onto the beach, moving sediment several metres inland (figure 9.2). Other sediments are taken away from the beach through ice-rafting when the ice foot breaks up.

On the coastal ice itself, there is an assortment of geomorphic features and activities, such as ice volcanoes and the erosion/deposition of ice by high-energy waves. These fascinating phenomena have little significance for the geomorphic changes to the beach and dune area.

9.1.4 Wave Action

Wave processes act directly on the beach during the early winter before the ice foot forms. The waves bring sediments to the beach, placing them where they can later be moved inland by wind. Very strong winds can drive waves tens of metres over the beach (figure 9.3). The water drains away when the sand is unfrozen but freezes in place when temperatures are below zero. The ice cover protects underlying sediments from aeolian deflation. Wave activity influences winter beach processes by shaping the berm before the sand freezes. Crest position and steepness of slope affect snow cover, wind erosion and deposition, and local runoff patterns.

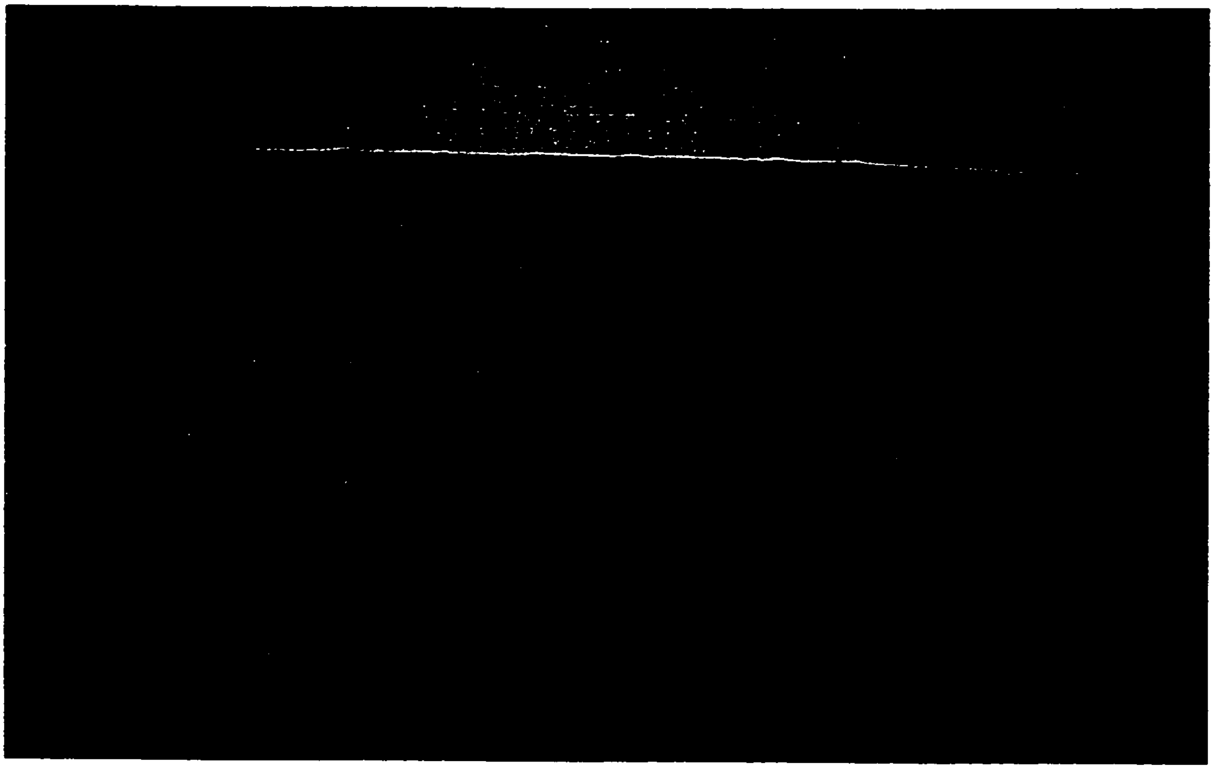


Figure 9.2 Ice-push features on Presqu'ile Beach, 28 January 1996

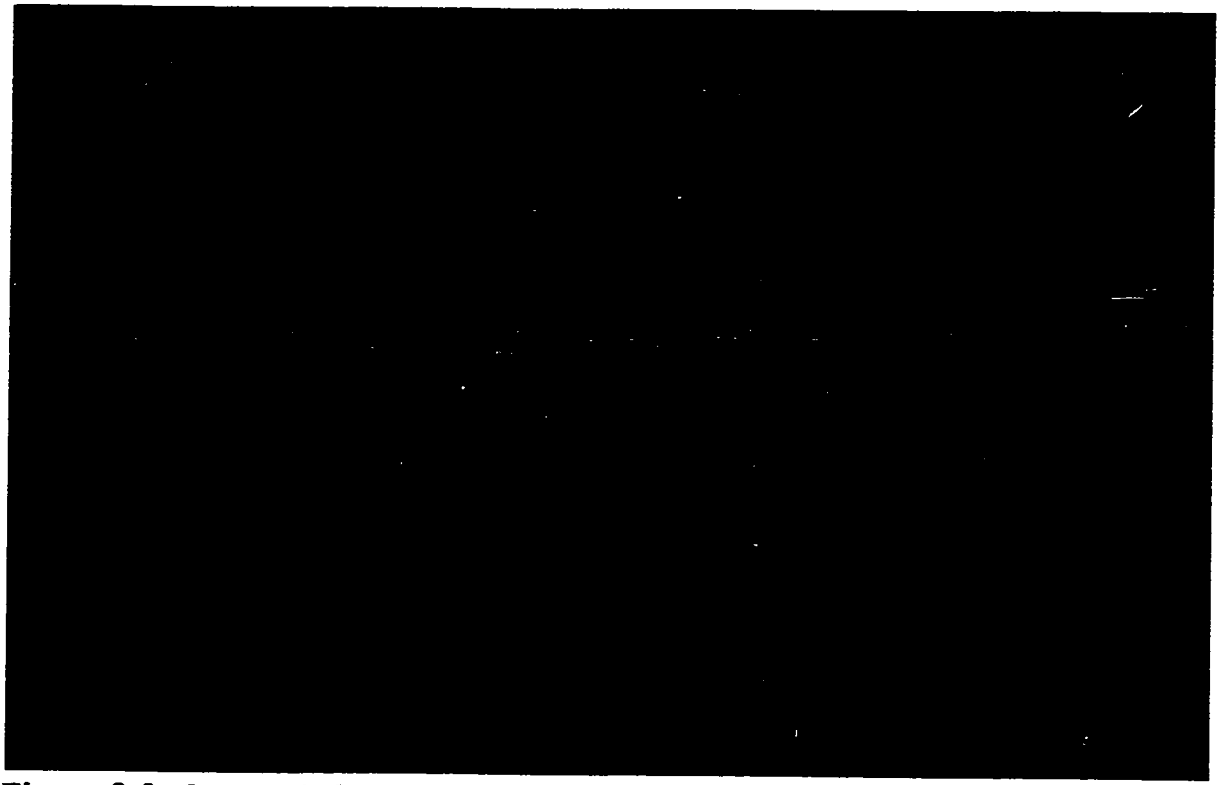


Figure 9.3 Overwash frozen onto the Presqu'ile Beach, 6 January 1997

9.1.5 Cold-Aeolian Activity

Cold-aeolian processes move sediments when winter conditions are suitable. The necessary conditions are temperatures below 0°C, wind speeds sufficient to move sediment, and exposed sources of sediment. Recorded sand movement and evidence of movement showed that cold-aeolian activity took place on a minimum of 19 and 25 days in the last two winters respectively (table 9.3). Large amounts of sand were trapped in December 1996 when the beach was free from snow and ice. The clear conditions did not occur again after surface ice formed in the end of December. Strong winds (>6 m/s at 1-metre height) were measured over the Presqu'ile Beach from 12% to 34% of the time, with the frequencies varying from month to month.

	December 15-31	January 1-31	February 1-28 (29)	March 1-15	total 90 (91)
1995-1996					
directly observed	n.a.	6	6	4	16
indirect evidence	n.a.	1	2	0	3
days with movement	n.a.	7	8	4	19
% frequency of 1-m wind speeds > 6 m/s	n.a.	16	14	19	16
1996-1997					
directly observed	4	6	4	3	17
indirect evidence	1	5	1	1	8
days with movement	5	11	5	4	25
trapped sand (kg, from dominant trap)	13.485	2.781	2.623	0.051	18.940
% frequency of 1-m wind speeds > 6 m/s	24	34	12	20	23

Table 9.3 Sand movement and frequency of strong winds measured at Presqu'ile Beach during the winters of 1995-1997

Sediment movement by wind changes beach and dune topography over the winter months. The wind transports sediments from west to east, eroding frozen sand from the western half of the beach and depositing sand behind the vegetation and foredunes to the east. Of the agents responsible for sediment movement--wind, water, ice, wave action--the wind moves sediments the greatest distances. Grains of sand can move up to 150 metres within the space of a few minutes. The wind transports large amounts of sand; more than 220 kilograms of sand per metre-width of beach moved towards the foredunes from December 1996 to March 1997 (this study, page 195).

9.1.6 Winter Patterns

Distinctive spatial patterns of erosion, protection and deposition occur on the Presqu'ile beach and dunes during winter. The characteristic pattern includes areas of exposed sand, surface ice, snow, and sand deposits. A typical profile from west to east has exposed sand near the ice foot, a shallow depression filled with ice, an exposed, slightly elevated midbeach ridge, ice in another shallow depression, an exposed or snow-covered upward slope to the base of the foredune, an exposed windward slope up to the dune crest, deep deposits of snow and sand to the lee of the dune, and snow/sand deposits extending to the parking lot (figure 9.4). During warm periods the surface ice is replaced by pools of water or combinations of ice and water.

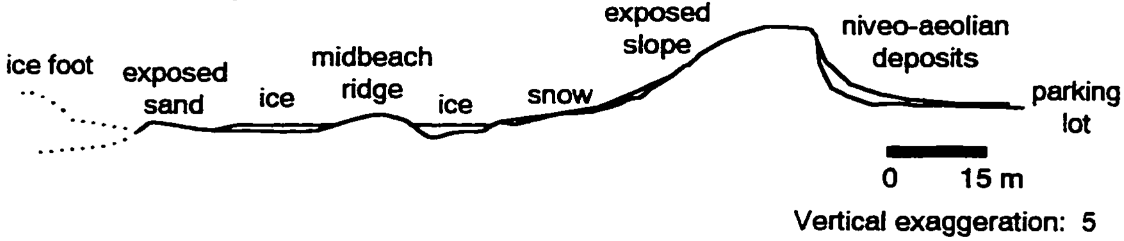


Figure 9.4 Sketch of characteristic winter profile, Presqu'ile Beach

The pattern of beach cover changed frequently from 15 December 1996 through 15 March 1997 as a result of precipitation, melting, and wind action (appendix D). The size of the various beach sections expanded or contracted as precipitation fell, melting occurred, the surface dried out, and wind moved snow and sediments inland. The record shows that the beach was entirely covered by snow and/or ice for 26 days out of the 91-day study period (figure 9.5a). In contrast, the beach was completely exposed (no surface ice or snow) for only 3 days in mid-December. For the rest of the time, exposed areas ranged from tiny patches near the ice foot to as much as 1140 m^2 (3-5 March) in more elevated beach areas.

Winter totals for beach cover are obtained by multiplying areas by the length of time the specific beach cover is present. By far the most prevalent type of beach surface was snow which existed for nearly 50% of the winter (figure 9.5b). Frozen sand was exposed for only 12% of the winter, which is equivalent to the entire beach being exposed for 11 days or 59 130 m^2 of sand exposed for one day. Patchy cover refers to mixtures of exposed sand, snow and/or ice; an assumption that a large part of the patchy cover was exposed still leaves less than 15% of the winter with exposed sand.

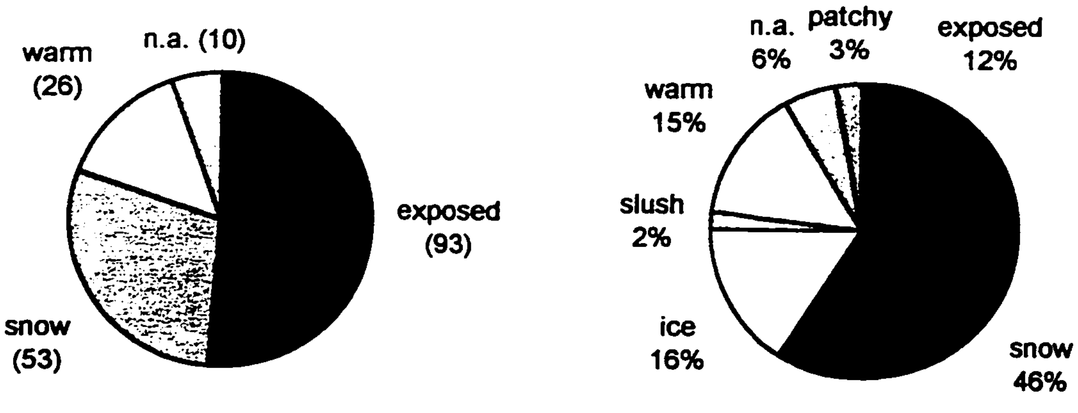


Figure 9.5 Occurrence of various beach covers during the 1996-1997 winter by a) half-day and b) square-metre per half-day equivalents

The study area was fairly representative of the entire Presqu'ile Beach. A few changes in spatial patterns were observed; for example, the midbeach ridge disappeared a few hundred metres to the south and was replaced by a continuous ice-/water-filled depression. For the rest, preferential areas of exposed sand were the strip of varying width beside the ice foot and the backbeach slope extending up to the foredune crest. Estimates of 10-15% exposure to cold-aeolian activity apply to the entire beach.

9.1.7 Winter Trends

A few trends stand out in the winter variability at Presqu'ile. Changes in beach cover and geomorphic processes respond to daily variations in the weather which is largely unpredictable. A general trend to an increasingly complex system is a pattern demonstrated winter after winter. Also characteristic is a general increase in frozen layer depth during the early winter and decrease in frozen layer thickness during late winter. The gradual development of a winter beach profile occurs as a combination of geomorphic processes shape the beach and dunes.

The trend from a simple to a complex beach occurs as precipitation inputs and processes are superimposed throughout the winter. At the onset of winter, the beach is a relatively simple system: an uninterrupted expanse of exposed (frozen) sand. Areas of ice and snow develop as the winter progresses and the beach becomes an aggregation of diverse surfaces. The different surfaces function as sediment sources, sediment sinks and protected surfaces. Measurement and prediction become difficult as the same processes and conditions do not occur over the whole beach. Dividing the beach into representative sections only works for defined time periods because the size and shape of beach areas change over the course of the winter.

There are a number of reasons for the Presqu'ile Beach not returning to a simple system over the course of the winter. Ground freezing plays a large role; drainage is restricted and the large inputs of water to the system are stored in various forms on the beach surface until they evaporate. Complete surface drying rarely occurs before more water is added to the system. Frequent changes in weather, including melt periods, snow and rain, prevent the beach from moving towards a stable condition. Changes and inputs are superimposed upon the beach which reflects a history of changes at different scales.

The general trend of freezing followed by thawing extends through the Presqu'ile winter. The development of the frozen layer takes place largely during the first half of the winter. The ground freezes from the top down, with frequent interruptions by periods of warmer temperatures. During the latter part of the winter, frozen layer development is halted and even reversed. There are many more days in which the top layer of the beach thaws at midday before refreezing for the night. Longer daylight hours and higher sun angles prompt a greater amount of melting and thawing. Sand movement by wind is generally restricted during those times.

Over the course of the winter, the beach and dunes develop a typical winter profile. The characteristic shape reflects erosion at the west end of the beach and deposition to the east of the foredunes. Dune shape is noticeably altered; steep scarps form as snow and sand is deposited. The niveo-aeolian deposits may be topped by cornices and have nearly vertical slopes. The history of aeolian movement is preserved in the layers of sand, snow and sand/snow mixes.

9.1.8 Geomorphic Change during the Presqu'ile Winter

Winter at Presqu'ile is divided into four categories relating to geomorphic processes on the beach and dunes (figure 9.6). Warm temperatures, during which water erosion is possible, account for roughly a quarter of the winter-time. Beach protection by snow and ice occurred during an additional 29% of the 1996-1997 winter. Varying amounts of exposed frozen sand are observed during the remaining time which was just over 50% during 1996-1997. When sand is exposed, pore-ice sublimation releases sediments which remain in place under low winds but move across the beach under strong winds. Sand moving winds combined with exposed sand were recorded at the Presqu'ile beach during 12% of the recent winter.

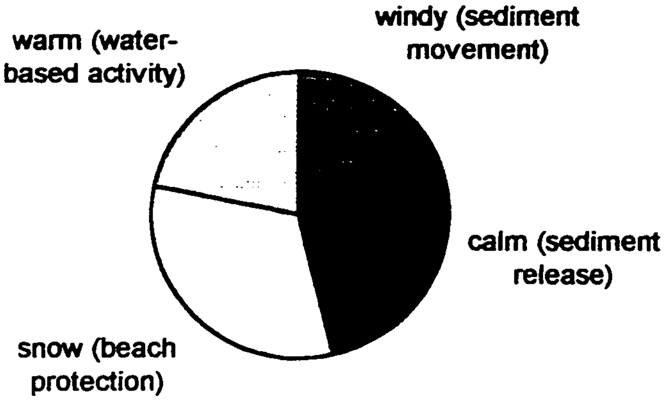


Figure 9.6 Presqu'ile Beach activities by winter conditions, 1996-1997

Sediment movement by waves, ice, water and wind occur at different scales and in different regions of the beach (figure 9.7). Resistance to movement takes the form of frozen sand cementation and the surface protection afforded by layers of snow and ice. The net result is sediment movement by waves or ice near the shoreline, sediment movement down-slope when water erosion is active, and sediment movement from west to east under the influence of wind. Topographic changes over the winter show beach deflation to the west and substantial deposition towards and over the dunes to the east. The evidence points to cold-aeolian activity dominating the geomorphic changes on the beach and dunes by moving the largest amounts of sand the longest distances.

9.2 Annual Beach and Dune Change at Presqu'ile

The winter processes fit into an annual cycle of beach and dune change. Spring thaws and rains rework the sediments which were deposited in winter. During the summer there is a natural lull in dune processes when the area receives less precipitation and weak winds. Precipitation and winds increase in the autumn as temperatures drop and deciduous vegetation begins to lose foliage. Aeolian activity resumes under the stronger

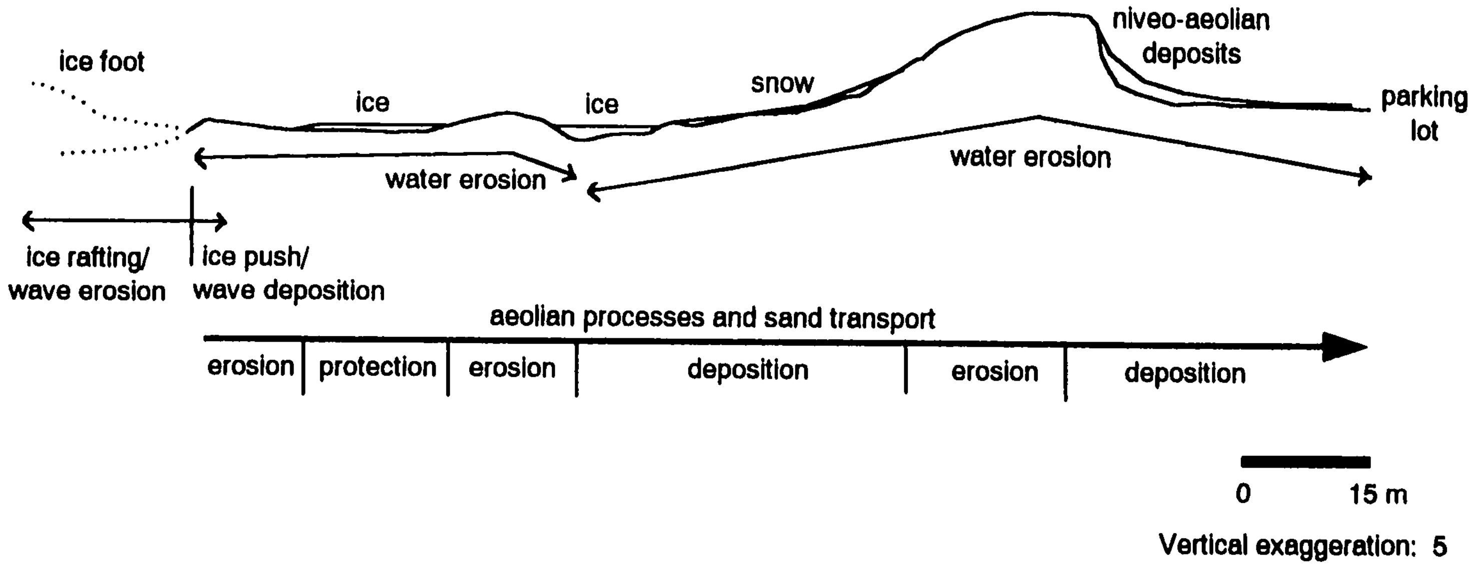


Figure 9.7 Sediment movement by ice, waves, water and wind on the Presqu'ile beach and dunes

winds, followed by cold-aeolian processes when temperatures fall below 0°C. The annual sequence of fall and winter movement, spring reworking and summer respite produce the cumulative changes which shape the beach/dune complex over the years and decades.

9.2.1 Geomorphic Activity in Spring

The Presqu'ile spring is characterized by melting snow and ice and the thawing of frozen ground. Large amounts of water are released into the beach and dune environment during the melt period. As long as a frozen layer remains at depth, the water is unable to drain into the ground. Surface runoff and pooling of water in depressions result. Water erosion features are frequently found on the beach as the runoff carves out drainage channels to low-lying areas.

Two milestones of the season are the disappearance of frozen ground and the break up of the ice foot. As the ground thaws, drainage through the sand is reestablished. The drainage enhances surface drying although high water levels can maintain midbeach pools of water until well into May or early June. Elevated areas of the beach dry more quickly. The lakeward edge of the beach changes noticeably with the demise of the ice foot and resumption of wave action. The waves deposit sediments on the beach and reshape the berm angle and crest position.

Winter deposits of sediments are reworked by water during the spring thaws. As snow melts in niveo-aeolian deposits, wet sand wrinkles and irregular denivation features result. The phenomena are ephemeral and quickly disappear during spring storms. Dune slopes undergo additional slumping and failure when thawed sand cannot maintain the steep winter angles of frozen snow and sand. Failure commonly takes place along the discontinuity between strongly-cemented frozen sand and the malleable wet sand of the surface.

The abundance of surface water inhibits aeolian processes in spring. Saturated sand resists entrainment by wind and pools of water protect large areas of the beach. Surface drying does occur during the periods of strong winds associated with spring storms. Movement of drier sediments follows the dominant wind direction from east to west.

The geomorphic activity of spring changes the harsh winter profile of the beach and dunes to more-rounded slopes. The principal geomorphic processes are water erosion, slope failure and wave action. Water erosion and slope failure rework sediments deposited in previous months and soften the severe slope angles produced by winter processes. Wave action reshapes the berm and resumes the deposition of sediment on the beach edge. The beach and dune shape emerging from spring activity remains present well into the following autumn.

9.2.2 Geomorphic Activity in Summer

Summer marks a lull in geomorphic processes on the beach and dunes. Warm temperatures continue to dry the beach sand, leaving at most a damp patch in the midbeach area. Precipitation has a yearly low in summer and there is little water available for surface erosion. The dunes are stabilized by as much as 100% vegetation on some east-facing leeward slopes (Law 1990, 75). Photoautotropic organisms also stabilize natural beach areas and dune surfaces during the warm summer months (Maxwell and McKenna Neuman 1994). At the lake edge, the beach continues to prograde as wave action quietly deposits sediments.

Little aeolian activity occurs during summer months despite the dry condition of the surface sediments. The relatively low summer wind speeds keep movement to a minimum and restrict the distances that wind-borne sand travels. Vegetation and algae also stabilize beach and dune surfaces, inhibiting sand transport by wind. Continuous sand trap measurements from June through August 1991 captured negligible amounts of sand (van Dijk 1993, 84). This contrasts sharply with the 220+ kilograms moved per metre-width during the 1996-1997 winter.

Park management practices produce the most noticeable landscape change during the summer months. Park staff regularly rake a recreational beach area to generate the pristine condition that recreational users expect. The raking removes algae and detritus from the surface and redistributes the sand to form a flat nonvegetated area 80-100 metres wide. The raking enhances evaporation, disrupts the normal establishment of vegetation and prevents the embryo dune development apparent on the natural sections of beach to the north and south (Maxwell and McKenna Neuman 1994, 222).

9.2.3 Geomorphic Activity in Autumn

The transition from summer 'calm' to the active winter environment occurs during the autumn months. During this time, precipitation and wind speeds increase as temperatures drop and deciduous vegetation dies back in preparation for the winter. Storm events bring strong winds, driving rains, and heavy wave activity in the nearshore zone. Each major storm noticeably alters beach shape and moves sediments onto the foredunes. Wet and rainy conditions inhibit sand movement, but the beach and dunes are well-drained in the absence of frozen sand and can dry out between precipitation events. Late autumn has conditions which are very similar to winter with less frequent freezing temperatures and snowfall.

Temporary ground freezing begins in late October or November. The early freezing is short-lived and affects only the top few centimetres of ground. The beach thaws completely in the periods of warmer temperature which follow. Prolonged periods of cold temperature in late fall can give winter conditions and activity an early start. 1995 is a notable example: the beach froze at the start of December and persistent cold temperatures deepened the frozen layer to more than forty centimetres in less than three weeks. These conditions were ideal for cold-aeolian activity because the ice and snow deposits of later winter had not yet developed.

The dominant geomorphic processes during autumn are sediment movement by waves and wind. High-energy storm waves shape the berm and shoreline, and occasionally waves wash over the berm crest to inundate large areas of the beach with water. The last storm before the beach freezes and the ice foot forms is responsible for generating the beach contours on which winter processes will act. During the autumn months, the frequency and magnitude of wind events increase and sediments are moved from the beach to the foredunes. Vegetation and algae do not prevent sediment movement: the vegetation is mostly deciduous and loses its foliage at this time of year (Law 1990), and the aggregation of sediments by algae is unable to resist abrasion by moving sand grains (Maxwell and McKenna Neuman 1994). Strong winds coupled with freezing temperatures produce significant amounts of cold-aeolian movement as the surface is usually free from snow and/or ice.

9.2.4 Cumulative Change on the Presqu'ile Beach and Dunes

Beach growth toward the west and sediment movement by wind towards the east produce the cumulative changes to the Presqu'ile beach and dunes. The Presqu'ile beach has been prograding by approximately two metres per year since 1949 (Law 1989b). Beach accretion is followed by the movement of the high-water mark to the west. In natural beach areas, vegetation establishes itself in the non-inundated zone and follows the westward progression of the high-water mark. The vegetation traps moving sand, forming an embryo dune which eventually develops into a foredune. The foredune captures moving sediments and downwind dunes stop growing and stabilize as their sand supply is cut off. In time, a new embryo dune forms at the westward-moving vegetation line and the cycle repeats itself.

The summer practice of beach raking interrupts the cycle of foredune growth and succession. Beach width is maintained far beyond the high-water mark, and vegetation is unable to establish itself in the raked area. The result is a large source area for wind-blown sediments which are transported towards the east. An artificially-inseminated foredune to the east is the sole recipient of the moving sand. Snowfences set up to protect beach parking lots from moving sand generated the dune which was further stabilized by the planting of marram grass. The dune grows by capturing moving sand each year and is in no danger of losing its sand supply as long as beach raking continues in the same location. The modified environments of beaches 1, 2, and 3 include this abnormally wide beach and fast-growing foredune.

9.3 Comparing Presqu'ile to Other Cold Regions

Various regions of the world have seasonally or permanently cold sediments which are exposed to aeolian processes. Direct measurements of sediment movement in these areas are rare, and there has been little field research related to active processes. The extensive field measurements at Presqu'ile during the cold season are important in this context of cold-aeolian research.

Quantitative field measurements and estimates of sediment release, deflation and transport are listed in table 9.4. The observations from Greenland, the North West Territories, northern Quebec, northern Michigan and Ontario are compared to predictions and measurements from Presqu'ile, Ontario. The table unfortunately illustrates how few quantitative measurements have been made.

McKenna Neuman has quantified sediment release from the frozen surface by pore-ice sublimation and proposed a model based on cold-laboratory tests without wind (McKenna Neuman 1990b, 1993). Predictions from McKenna Neuman's model using data for Pangnirtung Pass, N.W.T. are compared to Presqu'ile model predictions using similar data. Model predictions for -5°C are fairly close, putting the amounts of released sand well within the same order of magnitude. McKenna Neuman (1990b) noted that under saturated conditions, the predicted release at -30°C would be only 0.5% the predicted release at -5°C. A -30°C temperature combined with low wind speeds fell outside the range of the Presqu'ile model. Both models agree that particle release by sublimation decreases as temperatures become colder.

Frozen surface deflation by aeolian processes has been measured in Greenland (Riezebos *et al.* 1986) and at Presqu'ile (Law 1990; current study). Erosion pin measurements

Cold-Aeolian Research	Presqu'ile results
predicted sand release	**model predictions**
McKenna Neuman (1990b), N.W.T. (1) under calm conditions, saturated ground (33-36% water content by volume), 75% relative humidity, and -5°C air temperature, the model predicts 7.1 x 10^5 kg km^{-1} d^{-1} (2) under the same conditions but -30°C, the model predicts 3.7 x 10^3 kg km^{-1} d^{-1} (3) at -5°C with 10% volumetric moisture, the model predicts 2.46 x 10^6 kg km^{-1} d^{-1}	(1) with 2 m/s wind speed at 1-m height, 24% water content by weight, 75% relative humidity, -5°C ground temperature, the model predicts 9.2 x 10^5 kg km^{-1} d^{-1} (2) -30°C is outside model boundaries; no prediction is possible (3) with -5°C and 7% water content by mass, the model predicts 1.74 x 10^6 kg km^{-1} d^{-1}
deflation	**measured deflation (at erosion pins)**
Riezebos *et al.* (1986), Greenland 2 to 5 x 10^{-7} m during a winter windy dry period	3 to 9 x 10^{-4} m from 19-21 Dec 1996 3 to 10 x 10^{-4} m from 6-8 Jan 1997
Law (1990), Presqu'ile Beach up to 30 cm of sand during a single winter	0.6 to 2.1 cm during the 1996-97 winter
transport	**measured transport**
Riezebos *et al.* (1986), Greenland 100-250 kg of sediment during a winter dry windy period	19-21 December 1996 90 kg per m-width or 5400 kg for study area (3.3 m^3 of sand)
Marsh and Marsh (1987), northern Michigan +10 m^3 of sand from a cut created by a well-used footpath through the dunes	17-20 January 1997 17 kg per m-width or 1020 kg for study area (0.6 m^3 of sand)
Belanger and Filion (1991), northern Quebec 1.17 m^3 during 1987-1988	22-26 February 1997 17.5 kg per m-width or 1050 kg for study are (0.65 m^3 of sand)
	1996-1997 winter 13200 kg of sand (8.1 m^3)

Table 9.4 Quantitative measurements of cold-aeolian processes in various cold regions and at Presqu'ile Beach, Ontario

indicate that Presqu'ile deflation is 3 orders of magnitude larger than deflation estimated for a windy dry period during winter in Greenland. Riezebos *et al.* (1986) calculated deflation for their entire study area but snow-covered subsections may have reduced the total estimate. The 1996-1997 winter deflation at Presqu'ile is considerably less than earlier observations by Law (1990). The frequent warm temperatures and persistent snow-cover of 1996-1997 may contribute to the difference in results.

Studies in Greenland (Riezebos *et al.* 1986), Michigan (Marsh and Marsh 1987), Quebec (Belanger and Filion 1991) and Ontario (present study) have quantified the transport of sediment by wind. The measurements show that substantial amounts of sediment are moved by cold-aeolian activity in each of those environments. Direct comparison of the measurements is not possible because the study sites are different in areal extent.

Cold-aeolian activity at Presqu'ile has many characteristics which are distinctive to a mid-latitude, seasonally-frozen, sandy beach. Variability in temperature, including frequent warm periods, and significant amounts of rain and snow are particular to the middle latitude and coastal location. Presqu'ile's climate fosters sand movement with strong winter winds and relatively warm sub-zero temperatures; but the climate inhibits sand movement with frequent precipitation and thaw periods. The consistently high water content of the frozen surface also inhibits aeolian processes. The amounts and timing of sediment movement at Presqu'ile differ considerably from movement in areas with colder temperatures, less precipitation, drier sediments and longer freezing.

The Presqu'ile data make an important contribution to understanding cold-aeolian processes in all environments. Presqu'ile serves as an example of how much sediment can move under complex and variable conditions in similar seasonally-frozen coastal beach/dune complexes. For higher-latitude continental sand sheets, the Presqu'ile study illustrates the basic mechanisms of cold-aeolian activity which apply to all environments. The Presqu'ile study demonstrates that sediments are far from immobilized during the winter months and that substantial volumes of sand do move.

9.4 Cold-Aeolian Activity and Geomorphology

Cold-aeolian processes are largely ignored by mainstream geomorphology. Recent textbooks and discussion papers in aeolian geomorphology give little (Pye and Tsoar 1990) or no attention to cold regions (Sarre 1987; Chapman 1990; Sherman and Hotta 1990; Anderson, Sørenson and Willetts 1991; Nickling 1994; Livingstone and Warren 1996). General geomorphology and physical geography textbooks take even less notice of cold-aeolian activity. Brief sections on aeolian activity are often included in textbooks and discussion papers on permafrost and cold regions. This acknowledgement may stem from the personal experiences of cold-region researchers and/or aeolian evidence at field sites. Mainstream geomorphology has little regard for cold-aeolian research because studies lack integration with established aeolian transport models and direct observations of aeolian transport in cold settings are rare (McKenna Neuman 1993, 138).

The Presqu'ile study contributes both a coherent explanation of cold-aeolian activity and quantitative data to the discipline of geomorphology. The model, COLDAEOL.BAS, establishes an theoretical framework for cold-aeolian processes and clarifies process boundaries. As an alternative to established aeolian transport models which function in warm environments, the model can engage mainstream geomorphology in a discussion of why traditional models do not work in cold environments. Numerous gaps in cold-aeolian research are pointed out by the model as directions for further study, with the understanding that additional information will change and strengthen the model. The model is currently supported by quantitative data on deflation, transport and winter patterns of activity. These data make a valuable addition to the small body of work on cold-aeolian processes.

This study provides a unique contribution to coastal dune studies. Coastal dunes have been under-represented in traditional geomorphology because the environmental complexities are poorly understood (Carter, Nordstrom and Psuty 1990; Nordstrom, Carter and Psuty 1990). The Presqu'ile research explores the variability of the coastal environment and dune-forming processes. The study's unique contribution is the emphasis on seasonal processes and changes in temperate latitudes.

Supply-limitations in coastal environments have been receiving research attention lately, and the Presqu'ile study furnishes valuable information to this discussion. The numerous models which predict aeolian sediment transport rates assume transport-limited conditions under uniform steady flow and perform poorly in the beach environment where the air-flow is complex and sediment transport is usually supply-limited (Davidson-Arnott *et al.* 1997, 463-4). Field studies have shown that the potential transport is much greater than measured transport when moisture, short fetches, vegetation, etc., are part of the environment (Carter and Wilson 1990). The Presqu'ile study uses supply limitations to make more accurate predictions of transport over frozen surfaces. The same research methods may be fruitful when considered in other supply-limited environments.

9.5 Summary

The current study on cold-aeolian processes was physically based in Presqu'ile Provincial Park but can be understood and used in multiple contexts. During the Presqu'ile winter, cold-aeolian activity occupies a small portion of the time but is responsible for a major part of the geomorphological change. The distinct winter landscapes produced by cold-aeolian erosion and deposition are quite different from the landscapes of other season. The large amounts of sediment moved from the beach to the foredunes contributes to the long-term pattern of foredune growth and succession in natural areas. The Presqu'ile research adds quantitative data and a frame of reference to the body of research on cold-aeolian activity. This strengthens the position of cold-aeolian research within the discipline of geomorphology. The study methods and results have applications to coastal dune studies and considerations of supply-limitations in a variety of environments.

Chapter Ten

CONCLUSIONS

Still round the corner there may wait,
A new road, or a secret gate.
J.R.R. Tolkien

The experiments, data collection and analysis in this dissertation have produced a new model of cold-aeolian activity and original information on frozen sediments, pore-ice sublimation and winter sand movement at Presqu'ile. Conclusions from the research can be made about the various components of aeolian activity in cold regions and how they interact. Study conclusions are discussed in this chapter with respect to the objectives set out in chapter one. The research has practical applications for the Presqu'ile Beach study area as well as other cold regions which are influenced by aeolian activity. Research conclusions and applications highlight the significance of this study to cold-aeolian geomorphology.

10.1 Objectives and Conclusions

The dissertation research was designed to obtain quantitative information on the processes of sediment entrainment from frozen surfaces and to consolidate that information into a model of cold-aeolian activity. Specific objectives were outlined at the beginning of the study: 1) to look at supply limitations by defining frozen sediment influences on aeolian processes, 2) to look at supply mechanisms by defining sediment supply from frozen surfaces, 3) to incorporate supply limitations and mechanisms into a comprehensive model for cold-aeolian activity, 4) to test the model accuracy against field measurements and 5) to investigate the research context. Conclusions have been reached concerning all of the study objectives and are grouped under the headings 1) supply limitations, 2) sediment supply, 3) modelling cold-aeolian activity, 4) assessing model accuracy, and 5) multiple contexts.

10.1.1 Supply Limitations

Frozen sand cohesion, which limits sediment entrainment by wind, is exponentially related to water content. Pore-ice cohesion increases the resistance of frozen sand grains to movement by wind. Controlled experiments, measuring cohesion as a strength component only present in cohesive frozen samples, demonstrate that cohesion is strongly related to water content. Cohesion increases exponentially as the water content of frozen samples increase.

Water contents of 0-0.5%, 0.5-1%, and greater than 1% correspond to loose, weakly-cemented and strongly-cemented frozen sand, respectively. The specific water contents for classes of frozen sand were derived by experimentation because the data could not be found in existing literature. The results are important to identifying different conditions of frozen sand which undergo aeolian processes. The exponential relationship between water content and cohesion applies to the strongly cemented frozen sand; samples which had water contents below 1% were not cohesive enough for testing.

Loose, weakly-cemented, and strongly-cemented frozen sand permit unobstructed fluid entrainment, cohesion-limited fluid entrainment, and no fluid entrainment, respectively. The frozen sand descriptions provide a practical way for relating water content to distinct types of aeolian activity. Uncemented frozen sand (0-0.5% water content) has no increased resistance to fluid entrainment when winds exceed threshold velocities. Cemented grains are more resistant to wind and have greater thresholds for fluid entrainment. Instantaneous entrainment of cemented grains only occurs when cementation is weak (0.5-1% water content) and wind exceeds a cohesion-dependent threshold velocity. Strongly-cemented frozen sand cannot be directly entrained by wind because the resistance to movement is too large. Another method of releasing sand grains from the frozen surface is necessary before sand movement can take place.

Measured water contents from frozen sands on Presqu'ile Beach are high, indicating that direct fluid entrainment is not possible in this environment. Presqu'ile water contents measured at 6% to 35% by mass are well above the upper limit for direct entrainment. On the Presqu'ile Beach throughout winter, sediment movement by wind requires sand to be released from the frozen surface before it can be entrained by the wind.

Confining the fluid entrainment of frozen sediments to such a narrow range of water contents means that direct entrainment is unlikely in many cold regions. Like Presqu'ile, temperate coastal dunes and beaches can be expected to remain damp from the regular amounts of precipitation they receive during the cold season. Few cold-region studies make direct mention of surface water contents, but drier continental sand sheets and dunes can also be expected to exceed the very dry conditions required for instantaneous entrainment by strong winds. Such dry conditions do exist in a number of Antarctic regions where substantial amounts of sand movement take place.

10.1.2 Sediment Supply

Particle release from the frozen surface (L_w in kg m^{-2}) is governed by the equation

$$\begin{aligned} L_w = [\,&(0.052w^{-1.74})\,v + (0.43w^{-0.58})\,t \\ &- (0.15w^{-0.59})\,h + 17.1w^{-0.48}] \cdot 0.111 \end{aligned} \tag{10.1}$$

where w is water content (ratio of water to dry weight), V is wind speed (m/s at 1-m height), t is ground temperature (°C at 4-cm depth) and h is relative humidity (%). Semi-controlled experiments on the Presqu'ile Beach produced this equation for particle release under field conditions. The grains are released as sublimation depletes the pore ice which is cementing the frozen sand together. The rate of particle release is governed by the local microclimate (wind, temperature, relative humidity) and surface cohesion (water content).

The three microclimate variables--wind speed, temperature, and relative humidity--influence the rate of particle release by driving the process of sublimation. Temperature controls the resistance by molecular bonds to the process of water molecules detaching themselves from the solid and moving into the atmosphere; as temperature increases, the bonds are weaker and sublimation is encouraged. Relative humidity indicates how much room the atmosphere has for water molecules to move from the pore-ice surface; as relative humidity increases, the moisture gradient between surface and atmosphere becomes less steep and sublimation slows down. The wind removes water molecules from the boundary layer so that more molecules can move from the solid to the atmosphere. Wind also removes sediment from the surface so that the diffusion of water vapour is not inhibited. As wind speed increases, both water vapour and loose sediments are removed from the area and sublimation is encouraged.

The water content of the frozen surface has an inverse power function relationship with particle release. Field experiments indicated a logarithmic decrease in particle release with a logarithmic increase in water content ($r^2 = 0.88$ to 0.96). It is notable that the water content increase is exponential in this relationship. Earlier it has been shown that there is an exponential relationship between water content and cohesion. The similar pattern in results points to the increasing importance of water content at high levels in frozen sands.

On strongly-cemented frozen sands, the amount of sand released from the surface is the maximum amount of sand transported when movement takes place. Particle release is a prerequisite for sediment movement and transported sand cannot exceed the amount of particles released from the frozen surface. Particle release does not determine that sand grains will move; sufficiently strong winds are required before sediment movement can take place. During most periods of sand movement, the strong winds can carry substantially more sand than is available, and all of the particles which are released, are moved by wind. In these cases, a prediction of the amount of sand released also predicts the amount of sand that has moved.

10.1.3 Modelling Cold-Aeolian Activity

The concepts of sediment limits and supply are the foundation for a new model of cold-aeolian activity. In the traditional aeolian paradigm, sediment movement is understood and predicted from the wind's ability to transport particles. The new model switches the focus to the surface's ability to supply sediments for transport. When the wind exceeds a critical threshold, available sediment will be transported. The model assumption only works when the sediment supply is limited to the degree that it is always less than the amount the wind can transport. For frozen sand, this assumption holds true when the surface water content exceeds 1%.

Supply limitations include snow and ice cover as well as pore-ice in exposed frozen sands. Sediment protection by a superimposed layer of snow or ice is an important part of cold-season sand movement. The protection reduces the source area that supplies sediments to aeolian processes. The subsequent reduction in sand movement can be as much as 100% when the entire area is covered by snow or ice.

The computer program COLDAEOL.BAS is a reliable and practical form of the cold-aeolian model. The computer program is equipped to deal with many of the conditions that exist in cold environments. Model responses are determined by the input conditions of snow cover, ice cover, and sediments with water contents ranging from none to saturation. The model indicates what phenomena are active--beach protection, particle release, sand movement--and produces total amounts of released and transported sand. The computer program is an efficient tool for running multiple scenarios and considering extended time periods with large amounts of input data.

10.1.4 Assessing Model Accuracy

The comparison of erosion pin measurements to model predictions produced favourable results over a small dataset. Most of the model predictions of released sand were within the range of deflation measured at erosion pin sites. The agreement suggested that the model is reasonably accurate in its predictions. Variable conditions throughout the winter diminished the number of erosion pin measurements which could be used in the comparison, and the test results are based on a small amount of data.

The comparison of sand trap measurements to model predictions suggests that the model overpredicts sand release and transport, but the sand trap measurements are subject to a large degree of error. Model predictions of sand release and transport were consistently higher than deflation calculated from sand trap measurements. Error analysis of the trap measurements and computations suggest that the calculated deflation may severely underestimate actual deflation from beach surfaces. The uncertainty in the sand trap measurements leaves little confidence in the suggestion that the model overpredicts deflation.

The assessment of model accuracy is inconclusive and more field-testing is necessary. Erosion pin measurements suggest that the model is fairly accurate, but there are too few data to support that conclusion. Sand trap measurements taken at face value suggest that the model overpredicts; but detailed error analysis cast doubts on the calculations which form the basis for that statement. More field-testing is needed to produce strong conclusions about model accuracy. With the available research methods, an extensive program of erosion pin measurements will likely produce the most reliable results. Improvements to sand trap measurements and calculations would also be valuable as another test of model accuracy.

10.1.5 Multiple Contexts

Cold-aeolian activity is the dominant land shaping agent during winter on the Presqu'ile beach and dunes. Cold-aeolian activity is one of a number of geomorphic processes that are active during the winter months. Analysis indicates that cold-aeolian phenomena could occur during roughly 12% of the time from 15 December 1996 through 15 March 1997. Within that time frame, the aeolian processes moved more than 220 kg of sand per metre-width of study area from the western portion of the beach to the foredunes in the east. Other types of geomorphic activity moved smaller amounts of sediment and were limited to subsections of the beach/dune complex. Water-based sediment movement on the beach and dunes reworked sediments that had been moved and deposited by wind.

Cold-aeolian activity is an important component of annual beach and dune change. Net movement of sediment over the course of the year is from the beach to the dunes as a result of aeolian processes. This movement takes place primarily during the fall and winter and substantial amounts are moved by cold-aeolian processes. The sediment movement is supported by the progradation of the beach into Popham Bay as wave action deposits sediments on the beach edge.

Results from the Presqu'ile study site are important to aeolian research in other cold regions. The conclusions concerning supply limitations, supply mechanisms, and their interaction in the model contribute much to understanding cold-aeolian phenomena. The conceptual framework provided by the model defines the position of cold-region research within aeolian geomorphology and furnishes a number of take-off points for further research. Quantitative information on deflation, transport and winter patterns of activity are welcome additions to the meagre data on cold-aeolian activity world-wide.

The focus on sediment limits and supply is an important finding within the context of aeolian geomorphology. More situations exist in which the supply of sediments to aeolian processes is severely curtailed. Limitations to supply include moisture (non-frozen), algae, and surface crusts which form when soluble salts evaporate. In each case, sediment cohesion or cementation must be overcome in some fashion before movement can take place. On wet sediments, surface drying has many similarities to pore-ice sublimation in frozen sands. Crusts from algae or soluble salts produce surfaces more similar in cementation to frozen sand. These crusts are typically broken up by some form of disturbance before movement can take place.

10.2 Applications

This study of cold-aeolian activity has practical applications for Presqu'ile Provincial Park and other cold regions with similar processes. Within the provincial park structure, the research results are foundational to interpretation and management of the geomorphically-active beach and dune complex. The cold-aeolian model, and quantitative data obtained while producing the model, function as guides to understanding aeolian processes in various other cold regions. Concrete research questions arise from this study to be used as the basis for continued research into cold-aeolian processes.

10.2.1 Presqu'ile Provincial Park

The detailed information on cold-aeolian activity as a significant geomorphic process within Presqu'ile Provincial Park is extremely relevant to the Park's interpretive program. Winter observations, sand trap measurements, deflation rates, direction of movement and winter partitioning of various conditions furnish concrete details for the interpretation of beach and dune activity. The explanation of cold-aeolian mechanisms and processes contributes primary and up-to-date information on a topic which is unfamiliar to most people.

Presqu'ile Provincial Park has a unique opportunity to introduce cold-aeolian activity to the public. The beach and foredunes are tangible evidence of aeolian and cold-aeolian processes. Geomorphic change is current, measurable, and effects visible differences over timescales of days, months, and years. The location is rare in the sense that few cold-aeolian processes and landforms are as accessible to research and interpretation. Suitable access to the beach and dunes has made Presqu'ile the site of innovative techniques and quantitative field measurements from the early 1990's. As a result, the Presqu'ile beach and dunes have become a prominent site for research into cold-aeolian processes. Presqu'ile Provincial Park could capitalize on this success by sharing the research achievements with park visitors.

The data provided by this study on sediment movement and processes are relevant to park management of the beach and dunes. The Presqu'ile beach/dune complex is a geomorphically-active environment which also receives more than 100 000 visitors per year. Park management practices must balance visitor requirements with protecting the natural environment. The most significant management decisions in the context of dune formation have been beach raking and the development of an artificially-inseminated dune. Beach raking produces a wide vegetation-free source area for sediments during the winter months which is only partially offset by snow and ice cover. The artificially-inseminated foredune is a sink area for wind-blown sediments from the beach. Sediment supply to the dune (and subsequent dune growth) will continue as long as beach raking continue in the same location. The raked beach and foredune do not prevent natural sediment movement from occurring, but regulate the areas of deflation and deposition.

A proactive approach to management is suggested based on the understanding of sediment sources, sinks and movement. The eastern edge of beach raking determines the location of vegetation and subsequent deposition. This edge functions like the high-water mark on natural beaches except that the raked edge is fixed whereas the high-water mark follows beach progradation. Natural processes can be approximated by maintaining a specific beach width and moving the eastern edge of raking towards the lake as the beach progrades. Over time, the changing position of vegetation will encourage a natural sequence of dune growth to the east of the raked area. Recreational users will not lose beach area, and the sequence of dune birth, growth and succession can be utilized in the park's interpretive program.

10.2.2 Cold-Region Research

The cold-aeolian model introduces a theoretical framework for aeolian processes in all cold regions. The model clarifies process boundaries and indicates when sediment protection, release and deflation are likely to occur. The explanation of processes, supply limitations and interactions is invaluable as a rallying point for past and future research. Model components can be studied, refined and tested in the context of various cold environments. Model predictions provide quantitative estimates of sediment movement which can be compared to field measurements under a wide range of conditions.

Quantitative data from Presqu'ile Beach are important additions to the available records of cold-aeolian phenomena. The Presqu'ile data include transport rates and totals, deflation amounts, experimental measurements of sediment release under field conditions, patterns of erosion and deposition on a mid-latitude freshwater coast, surface variations and water content measurements. The measurements are necessary to support process explanations and to illustrate the role of aeolian activity in cold seasons and environments.

The results of this dissertation suggest practical directions for cold-aeolian research (table 10.1). Many aspects of cold-aeolian phenomena remain poorly understood. More research is needed on how the properties of frozen sediments relate to aeolian processes. In particular, the relationship between threshold velocities and the entrainment of weakly-cemented frozen sediments has not yet been explored. Particle release from frozen surfaces is better understood, but there remains room for additional study. On a broader scale, the cold-aeolian model needs to be tested and refined to function in diverse cold regions. New measurement and analysis techniques for cold regions require further development. The Presqu'ile beach and dunes are an accessible location for studies on cold-aeolian research methods and processes, and a number of specific research questions can be applied to the area.

Conceptual questions of how cold-aeolian research fits into (aeolian) geomorphology are very important despite their exclusion from table 10.1. Investigators must address the gap between mainstream geomorphology and processes which are important in conceptually-marginalized areas. The integration of cold-aeolian research with established aeolian transport models requires an understanding of the relationship between supply-limited and transport-limited processes. Better ties between the research areas will raise the intellectual profile of cold-aeolian activity and stimulate fresh concepts in aeolian and coastal geomorphology.

10.3 Research Significance

The geomorphological research described in this dissertation is significant as one of the rare field studies of cold-region aeolian activity. Innovative techniques were developed to sample frozen sediments and sand transport under cold conditions. The detailed field program of measurements and experiments produced a substantial body of quantitative

Suggested Research Topics
Frozen Sediments
Additional studies to confirm boundaries for frozen sand descriptions based on water contents.
Experiments to test grain size and shape effects on frozen sand descriptions.
Fluid Entrainment from Frozen Sediments
Empirical and theoretical studies to find threshold shear velocity on frozen sands between 0.5% and 1% water content
Experiments to determine grain size and shape effects on thresholds within the same water content range
Grain Release from Frozen Sediments
Empirical and theoretical studies to verify equation 6.7 and expand the range of conditions to which the equation can be applied
Empirical studies to test the effects of grain size and shape on sublimation-induced release from the frozen surface
The Cold-Aeolian Model (COLDAEOL.BAS)
Further empirical studies to test the accuracy of the model in a variety of cold regions
Examination of whether the model can be partitioned to account for varying surface covers over the study area
Winter Sand Trap Measurements
Testing of winter sand trap efficiency and trap modification to improve efficiency
Examination of the relationship between sand trap measurements and surface deflation
Examination of the concept of effective fetch (where is trapped sand coming from and how do non-continuous surfaces affect trap data?)
Presqu'ile-Specific Research
Continued measurement of cold-aeolian transport over the beach (with sand traps)
Detailed comparison of 1) autumn vs. winter transport and 2) warm vs. cold transport throughout the autumn and winter
Empirical studies of cold-aeolian deflation; more erosion pin measurement sites including deflation measurements closer to the ice foot
Mapping moisture variations on beach throughout winter (is the water content really as consistently high as this study suggests?)
Comparison of winter vs. long-term movement
Application of model to additional winters

Table 10.1 Directions for future research

information about processes, patterns and geomorphic change. These data are original to the Presqu'ile study area and, in many cases, the world. A conservative estimate suggests that geomorphology's quantitative database for cold-aeolian phenomena doubled through the investigations of this study. The new methodologies and techniques will benefit ongoing research at Presqu'ile along with studies in other cold environments.

The dissertation makes a significant contribution to geomorphology in the original model for cold-aeolian activity. The model integrates quantitative data and explanation as it predicts particle release and transport based on microclimate and surface conditions. Model assumptions that supply limitations restrict movement and supply mechanisms govern transport ensure that the model is realistic in the complex coastal environment. Model concepts have practical applications to understanding geomorphic processes within Presqu'ile Provincial Park and in other cold regions. Directions for future research are clarified in the light of model results and limitations. Finally, the model has theoretical significance in its potential to place cold-aeolian activity on the geomorphological map.

APPENDIX A

List of Symbols

A	dimensionless coefficient in Bagnold's threshold equation; $A \approx 0.1$ (p. 32)
	dimensionless shear stress in the dimensionless threshold shear velocity equation by Iversen *et al.*, 1987 (p. 32)
	cross-sectional area (p. 101)
A_n	dimensionless threshold velocity
a	moment arm, $a = (d/2)\cos\varphi$
b	moment arm, $b = (d/2)\sin\varphi$
C	cohesion
CG	centre of gravity
C_s	shape coefficient such that $C_s d^3$ is the volume of the grain (for a sphere, $C_s = \pi/6$)
C_L	coefficient of lift
d	particle diameter
F_c	capillary force
F_d	fluid drag
F_L	lift force
G	term related to geometric properties of contacts between soil particles
g	gravitational acceleration
h	12-hour average of relative humidity
I_w	function of the evaporation rate
i_c	critical pore ice content
k	von Karmon's constant (=0.41)
k_s	thermal conductivity
L_w	12-hour weight of particles deflated from a frozen surface with water content w
P	pivot point (p. 30)
	pressure deficiency (p. 38)
	applied load (p. 101)
Δp	pressure difference between top and bottom of a sphere
Q	sand transport in kg $m^{-2(12\text{-hour})}$-1
Q^g	soil heat flux
q	particle transport rate or sediment flux
q_u	unconfined compressive strength
S_a	aggregate stability
s/c	(soluble) salt content in mg salt per gram of soil
s_u	shear strength
T	surface tension of the water
	mean soil temperature
t	12-hour average temperature
u	wind fluid velocity measured 0.35d above the theoretical surface represented by z_0
u_*	shear or friction velocity
u_{*t}	threshold shear (or friction) velocity

u_{*tf}	threshold shear (or friction) velocity for a frozen surface
u_{*tw}	threshold shear velocity (or friction) for a wet surface
V	wind speed at a height of one metre
V_t	threshold wind speed at a hiehgt of 1 metre
v	12-hour average wind speed at a height of 1 metre
v_p	abrading particle's velocity
W	submersed particle weight (p. 30)
	abrasive erosion (p. 111)
w	moisture content (% dry weight)
w_c	critical moisture content
w_i	pore ice content (frozen moisture)
w_l	limiting moisture content
w_{subl}	moisture content of pore ice to be sublimated
z_0	roughness height
α	angle of impact
β	coefficient based on relative position of grain in bed, turbulence and the height of drag force action (p. 31)
	particle resting angle (p. 37)
π	pi = 3.14159...
ρ	density of air (ρ_a)
σ	density of the particle (ρ_s)
	normal stress at failure
σ_c	compressive stress
τ	shear stress
τ_c	critical shear stress
ϕ'	angle of repose of a grain (friction angle)
φ	angle that pivot point (P) and weight (W) form through center of gravity (CG)

APPENDIX B

Research Data-Sheets

O-1	Observation sheet for cohesion of frozen sand
UCT-1	Unconfined compression test data-sheet
S-1	Soil moisture data-sheet
C-1	Cementation test data-sheet
G-1	Ground sublimation experiments data-sheet
G-2	Ground sublimation experiments: moisture content data-sheet
EP-1	Erosion pin measurement data-sheet
W-1	Winter sand trap data-sheet

Cohesion of Frozen Sand by Moisture Content - Data Sheet

Name ______________________ Date ________________ Test No. ______________

Temperature ________ Date and time samples were put into freezer ______________

Description of samples ____

____

Test Data

Sample #	% Moisture (mixed)	Time	Observations	% Moisture (dried)

UCT-1

Name Date Test No:

Sample # Moisture: (mixed) (measured)

Test Details

	1	2	3
Sample Length			
Sample Diameter			

Strain Rate: Start
End

Load Dial: Start Anomalies
End Time

Final Shape
(measurements)

Time	Load	Strain

Soil Moisture Data Sheet

S-1

Site #	Wet weight with tin	Dry weight with tin	Weight of tin	Moisture content	Date: Comments

Cementation Test Data Sheet C-1

block #	$H_20_{(d)}$ (g)	calc. % moist.	p-test kg/cm^3	loose (clumps)	fingers	foot	hammer	no break	meas. % moist.	comments: (class)

Ground Sublimation Experiments Data Sheet G-1

Block #	%	PM: weight of block	AM: weight of block	Weight of loose sand	Final moisture	Comments	
A1							
A2							
A3							
A4							
A5							
A6							
B1							
B2							
B3							
B4							
B5							
B6							
A1							
A2							
A3							
A4							
A5							
A6							
B1							
B2							
B3							
B4							
B5							
B6							

Ground Sublimation Experiments: Moisture Content

G-2

Block #	%	Wet weight with tin	Dry weight with tin	Weight of tin	Moisture content	Comments
A1						
A2						
A3						
A4						
A5						
A6						
B1						
B2						
B3						
B4						
B5						
B6						
A1						
A2						
A3						
A4						
A5						
A6						
B1						
B2						
B3						
B4						
B5						
B6						

Erosion Pin Measurements Data Sheet EP-1

date/ conditions	1	2	3	4	5	6	7	8	9

Winter Sand Trap Data Sheet

W-1

date/time and conditions	A (W)	B (NW)	C (N)	D (NE)	E (E)	F (SE)	G (S)	H (SW)

APPENDIX C

Computer Program: COLDAEOL.BAS

```
100 n = 0
110 Ltotal! = 0
115 Lrun = 0
120 Lsum = 0
130 Qtotal! = 0
140 warmperiod = 0
150 meltperiod = 0
160 iceperiod = 0
170 snowperiod = 0
180 nperiod = 0
190 Lperiod = 0
200 Qperiod = 0

250 CLS 0 'clear screen
260 REM title screen
270 PRINT
280 PRINT
290 PRINT "Welcome to the Cold-Aeolian Computer Simulation."
300 PRINT
310 PRINT
320 PRINT "This program predicts aeolian activity in cold environments,"
330 PRINT "based on microclimate and surface conditions."
340 PRINT
350 PRINT
360 PRINT "The simulation works with time periods of 12 hours each."

400 REM keyboard or file?
410 PRINT
420 PRINT "You have the option of being prompted for data from the keyboard "
430 PRINT "or running the simulation on data in a separate file."
440 GOTO 460 'skip wrong input prompt
450 GOSUB 9500 'wrong input prompt
460 PRINT
470 INPUT "Please choose 1 for keyboard input, 2 for file:  ", alpha
480 IF alpha = 1 THEN GOTO 2940 'keyboard input
490 IF alpha <> 2 THEN GOTO 450 'improper response

600 REM data from file
605 CLS 0
610 PRINT
620 PRINT "A data file must have the following format"
630 PRINT "[variable specifications are given in brackets]:"
640 PRINT "label, air temperature [deg C], average net radiation [W/m2],"
650 PRINT "maximum net radiation [W/m2], ice [0=none, 1=present], snow [0=none,"
660 PRINT "1=present], wind speed [at 1 m height in m/s], ground temperature"
670 PRINT "[at 4 cm depth in deg C], water content [%], relative humidity [%]."
680 PRINT "Data should be separated by commas only."
690 PRINT
700 INPUT "Enter filename:  ", n$
710 OPEN n$ FOR INPUT AS #1
720 INPUT "Enter new filename for output data:  ", m$
730 OPEN m$ FOR OUTPUT AS #2
740 WRITE #2, "label, n, warm, melt, ice, snow, nomovement, sublimation, L!,
        Ltotal!, Lsum, movement, Q!, Qtotal!"
750 CLOSE #2
760 PRINT
```

```
770 PRINT
780 PRINT "********************Program is running********************"

1000 REM line of data from file and calculations
1010 IF (EOF(1)) <> 0 THEN GOTO 9000 'simulation summary
1020 INPUT #1, label, temp, avenet, maxnet, ice, snow, wind, groundtemp,
        watercontent, relhum
1030 water = watercontent / 100
1035 area = 1
1040 IF groundtemp > 0 THEN groundtemp = 0

1045 n = n + 1
1050 Q! = 0
1055 L! = 0

1060 IF temp < 0 THEN GOTO 1120

1065 REM temperature above zero
1070 warm = 1
1075 warmperiod = warmperiod + 1
1080 Ltotal! = 0
1090 Lrun = 0
1100 GOSUB 9400 'write results to file
1110 GOTO 1000 'new line of data

1120 IF avenet < 0 THEN GOTO 1150

1125 REM average net radiation above zero
1130 melt = 1
1135 meltperiod = meltperiod + 1
1140 GOTO 1170 'skip maxnet indication of melting

1150 IF maxnet < 100 THEN GOTO 1170

1155 REM maximum net radiation above 100
1160 melt = 1
1165 meltperiod = meltperiod + 1

1170 IF ice < 1 THEN GOTO 1230

1175 REM surface covered with ice; no movement
1180 ice = 1
1185 iceperiod = iceperiod + 1
1190 Ltotal! = 0
1200 Lrun = 0
1210 GOSUB 9400 'write results to file
1220 GOTO 1000 'new line of data

1230 IF snow < 1 THEN GOTO 1290

1235 REM surface covered with snow; no movement
1240 snow = 1
1245 snowperiod = snowperiod + 1
1250 Ltotal! = 0
1260 Lrun = 0
1270 GOSUB 9400 'write results to file
1280 GOTO 1000 'new line of data

1290 IF watercontent > .5 THEN GOTO 1390
```

```
1295 REM water content below 0.5%
1300 IF wind > 6 THEN GOTO 1340
1305 REM wind speed below 6 m/s; no sand movement
1310 nomove = 1
1312 nperiod = nperiod + 1
1315 Ltotal! = 0
1320 Lrun = 0
1325 GOSUB 9400 'write results to file
1330 GOTO 1000 'new line of data
1335 REM wind speed above 6 m/s; sand movement
1340 Q! = .000004 * (wind - 6) ^ 3
1345 move = 1
1350 Qtotal! = Qtotal! + Q!
1360 Qperiod = Qperiod + 1
1365 Ltotal! = 0
1370 Lrun = 0
1375 GOSUB 9400 'write results to file
1380 GOTO 1000 'new line of data

1390 IF watercontent > 1 THEN GOTO 1700

1395 REM water content between 0.5 and 1 %
1400 IF wind < (20 * watercontent - 4) THEN GOTO 1490
1405 REM direct entrainment
1410 Q! = .000004 * (wind - 6) ^ 3
1420 IF Ltotal! > 0 THEN Ltotal! = Ltotal! - Q!
1430 IF Ltotal! < 0 THEN Ltotal! = 0
1440 IF Ltotal! = 0 THEN Lrun = 0
1445 move = 1
1450 Qtotal! = Qtotal! + Q!
1460 Qperiod = Qperiod + 1
1470 GOSUB 9400 'write results to file
1480 GOTO 1000'new line of data
1485 REM sublimation then entrainment
1490 IF Ltotal! < 14 THEN S = 1
1500 IF Ltotal! > 14 THEN S = 2
1510 IF Ltotal! > 28 THEN S = 3
1520 IF Ltotal! > 42 THEN S = 4
1530 L! = 1 / S * .111 * ((.052 * water ^ -1.74) * wind + (.43 * water ^ -.58)
        * groundtemp - (.15 * water ^ -.59) * relhum + 17.1 * water ^ -.48)
1540 IF wind > 6 THEN GOTO 1610
1545 REM wind too weak to remove loose sand
1550 Ltotal! = Ltotal! + L!
1560 Lsum = Lsum + L!
1565 sublim = 1
1570 Lperiod = Lperiod + 1
1580 Lrun = Lrun + 1
1590 GOSUB 9400 'write results to file
1600 GOTO 1000 'new line of data
1605 REM wind removes loose sand
1610 L! = L! * S'dried layer no longer affects sand release
1615 Q! = L!
1620 Qtotal! = Qtotal! + L! + Ltotal!
1630 Lsum = Lsum + L!
1640 Ltotal! = 0
1650 Lrun = 0
1655 sublim = 1
1660 Lperiod = Lperiod + 1
1665 move = 1
1670 Qperiod = Qperiod + 1
```

```
1680 GOSUB 9400 'write results to file

1690 GOTO 1000 'new line of data

1695 REM water content above 1 %
1700 IF Ltotal! < 14 THEN S = 1
1710 IF Ltotal! > 14 THEN S = 2
1720 IF Ltotal! > 28 THEN S = 3
1730 IF Ltotal! > 42 THEN S = 4
1740 L! = 1 / S * .111 * ((.052 * water ^ -1.74) * wind + (.43 * water ^ -.58)
          * groundtemp - (.15 * water ^ -.59) * relhum + 17.1 * water ^ -.48)
1750 IF wind > 6 THEN GOTO 1820
1755 REM wind too weak to remove loose sand
1760 Ltotal! = Ltotal! + L!
1770 Lsum = Lsum + L!
1775 sublim = 1
1780 Lperiod = Lperiod + 1
1790 Lrun = Lrun + 1
1800 GOSUB 9400 'write results to file
1810 GOTO 1000'new line of data
1815 REM wind removes loose sand
1820 L! = L! * S 'dried layer no longer affects sand release
1825 Q! = L!
1830 Qtotal! = Qtotal! + L! + Ltotal!
1840 Lsum = Lsum + L!
1850 Ltotal! = 0
1860 Lrun = 0
1865 sublim = 1
1870 Lperiod = Lperiod + 1
1875 move = 1
1880 Qperiod = Qperiod + 1
1890 GOSUB 9400 'write results to file
1900 GOTO 1000 'new line of data
1910 GOTO 9000

2000 GOTO 2020 'skip wrong input prompt
2010 GOSUB 9500 'wrong input prompt
2015 PRINT
2020 INPUT "Press <ENTER> to continue.  ", delta
2025 CLS 0
2030 PRINT
2040 PRINT "You have completed "; n; " 12-hour simulation(s)."
2050 PRINT "Would you like to:"
2060 PRINT "      1) Summarize simulation."
2070 PRINT "      2) Add another 12-hour simulation."
2080 PRINT "      3) Start over from the beginning."
2090 PRINT "      4) Exit."
2100 INPUT "Please type '1', '2', '3', or '4': ", beta
2110 IF beta = 1 THEN GOTO 9000 'simulation summary
2120 IF beta = 2 THEN GOTO 2940 'begin another simulation
2130 IF beta = 3 THEN GOTO 100 'start of program
2140 IF beta = 4 THEN GOTO 9900 'end of program
2150 GOTO 2010 'improper response

2940 PRINT
2950 PRINT "You have the opportunity to indicate the area for the simulation."
2960 PRINT "Results will also be given for a square metre area."
2970 PRINT "If you do not have a larger study area in mind, you can enter"
2980 PRINT "a default value of 1."
2990 INPUT "Area (in square metres):  ", area
```

```
3000 n = n + 1
3010 INPUT "What is the air temperature in degrees Celsius?  ", temp
3020 IF temp > 0 THEN
        PRINT
        PRINT "In this 12-hour period, the processes are not cold aeolian"
        PRINT "because the temperature is too warm."
        IF Ltotal! > 0 THEN GOSUB 9700
        warmperiod = warmperiod + 1
        GOTO 2000 'completion screen
3030 END IF
3040 PRINT
3045 INPUT "What is the average net radiation (in W/m2)? ", avenet
3050 IF avenet > 0 THEN
        PRINT
        PRINT "There may be melting of surface pore ice despite"
        PRINT "below-zero temperatures."
        meltperiod = meltperiod + 1
        GOTO 3220 'next phase
3060 END IF
3070 PRINT
3080 INPUT "What is the maximum net radiation (in W/m2)? ", maxnet
3090 IF maxnet > 100 THEN
        PRINT
        PRINT "There may be melting of surface pore ice despite "
        PRINT "below-zero temperatures."
        meltperiod = meltperiod + 1
3100 END IF

3200 GOTO 3220 'skip wrong input prompt
3210 GOSUB 9500 'wrong input prompt
3220 PRINT
3230 PRINT "Please indicate whether the ground is covered with ice. "
3240 INPUT "0 for no, 1 for yes:  ", ice
3250 IF ice = 0 THEN GOTO 4000 'next phase
3260 IF ice = 1 THEN GOTO 3280 'skip improper response
3270 GOTO 3210 'improper response
3280 PRINT
3290 PRINT "Surface ice protects the frozen ground and no aeolian"
3300 PRINT "movement of sand occurs.  Sublimation gradually reduces"
3310 PRINT "the amount of surface ice."
3320 IF Ltotal! > 0 THEN GOSUB 9700
3330 iceperiod = iceperiod + 1
3340 GOTO 2000 'completion screen

4000 GOTO 4020 'skip wrong input prompt
4010 GOSUB 9500 'wrong input prompt
4020 PRINT
4030 PRINT "Please indicate whether the ground is covered with snow."
4040 INPUT "0 for no, 1 for yes:  ", snow
4050 IF snow = 0 THEN GOTO 5000 'next phase
4060 IF snow = 1 THEN GOTO 4080 'skip improper response
4070 GOTO 4010 'improper response
4080 PRINT
4090 PRINT "Snow cover protects the frozen ground and no aeolian"
4100 PRINT "movement of sand occurs."
4110 PRINT
4120 INPUT "Please enter the wind speed (in m/s):  ", wind
4130 GOTO 4150 'skip wrong input prompt
4140 GOSUB 9500 'wrong input prompt
```

```
4150 PRINT
4160 PRINT "Please choose a snow category:"
4170 PRINT "     1.  Freshly fallen snow, dry or fluffy"
4180 PRINT "     2.  Older snow, wet, heavy, firmly packed or dense"
4190 INPUT "Your selection:  ", snowfactor
4200 IF snowfactor = 1 THEN
        IF wind < 4 THEN
                GOTO 4250 'output to screen
        ELSE
                PRINT
                PRINT "Blowing snow occurs as wind moves snow from the area."
                IF Ltotal! > 0 THEN GOSUB 9700
                snowperiod = snowperiod + 1
                GOTO 2000 'completion screen
        END IF
4210 END IF
4220 IF snowfactor = 2 THEN
        GOTO 4250 'snow not moving
4230 END IF
4240 GOTO 4140 'improper response
4250 PRINT
4260 PRINT "Winds are not strong enough to move snow from the area,"
4270 PRINT "but sublimation of snow occurs."
4280 IF Ltotal! > 0 THEN GOSUB 9700
4290 snowperiod = snowperiod + 1
4300 GOTO 2000 'completion screen

5000 PRINT
5005 PRINT "Please enter the following information in the units specified."
5010 INPUT "Average wind speed (at 1 m height in m/s)?  ", wind
5020 INPUT "Ground temperature (at 4 cm depth in degrees Celcius)?  ",
       groundtemp
5025 IF groundtemp > 0 THEN groundtemp = 0
5030 INPUT "Water content (in percent)?  ", watercontent
5040 water = watercontent / 100
5050 INPUT "Relative humidity (in percent)?  ", relhum

6000 REM water content < 0.5 %
6010 IF watercontent > .5 THEN GOTO 7000 'next phase
6020 PRINT
6030 PRINT "Frozen sand is uncemented and there is an unlimited supply"
6040 PRINT "of sand for aeolian processes."
6050 IF wind > 6 THEN GOTO 6110 'output and calculations
6060 PRINT
6070 PRINT "During the 12-hour period, wind speeds were too low for"
6080 PRINT "sand to move."
6085 IF Ltotal! > 0 THEN GOSUB 9600
6090 nperiod = nperiod + 1
6100 GOTO 2000 'completion screen
6110 PRINT
6120 PRINT "The average wind speed exceeded the threshold for movement"
6130 PRINT "during this 12-hour period."
6140 Q! = .000004 * (wind - 6) ^ 3
6160 PRINT
6170 PRINT Q!, "kg of sand per square metre were removed by the wind"
6180 IF area > 1 THEN PRINT "for a total of "; Q! * area; " kg over the ";
       area; " square metre area."
6185 IF Ltotal! > 0 THEN GOSUB 9600
6190 Qtotal! = Qtotal! + Q!
6200 Qperiod = Qperiod + 1
```

```
6210 GOTO 2000 'completion screen

7000 REM 0.5 % < watercontent < 1 %
7010 IF watercontent > 1 THEN GOTO 8000 'next phases
7020 PRINT
7030 PRINT "Frozen sand is cohesive but not strongly cemented by pore ice."
7040 IF wind > (20 * watercontent - 4) THEN
        PRINT
        PRINT "Wind speeds were high enough to directly entrain sand"
        PRINT "grains from the frozen surface."
        Q! = .000004 * (wind - 6) ^ 3
        PRINT
        IF Ltotal! > 0 THEN GOSUB 9800
        PRINT
        PRINT Q!, "kg of sand per square metre were removed by the wind"
        IF area > 1 THEN PRINT "for a total of "; Q! * area; " kg over the ";
                area; " square metre area."
        Qtotal! = Qtotal! + Q!
        Qperiod = Qperiod + 1
        GOTO 2000 'completion screen
7050 ELSE
        PRINT
        PRINT "However, wind speeds were not high enough to directly entrain"
        PRINT "grains from the frozen surface, and pore-ice sublimation was"
        PRINT "necessary to release sand for movement."
        GOTO 8050 'calculations for sand release and transport
7060 END IF

8000 REM watercontent > 1 %
8010 PRINT
8020 PRINT "Frozen sand is firmly cemented by pore ice. Sand grains are only"
8030 PRINT "available for movement when they have been released from the"
8040 PRINT "surface by pore-ice sublimation."
8050 IF Ltotal! < 14 THEN S = 1
8055 IF Ltotal! > 14 THEN S = 2
8060 IF Ltotal! > 28 THEN S = 3
8065 IF Ltotal! > 42 THEN S = 4

8070 L! = 1 / S * .111 * ((.052 * water ^ -1.74) * wind + (.43 * water ^ -.58)
        * groundtemp - (.15 * water ^ -.59) * relhum + 17.1 * water ^ -.48)

8080 IF wind > 6 THEN GOTO 8240 'calculations and output
8090 PRINT
8100 PRINT "During this 12-hour period, wind speeds were too low for sand"
8110 PRINT "to move."
8120 PRINT
8130 PRINT L!, "kg of sand per square metre were released from the"
8140 PRINT "frozen surface by pore-ice sublimation"
8150 IF area > 1 THEN PRINT "for a total of "; L! * area; " kg over the"
8160 PRINT area; " square metre area."
8170 IF Lrun > 0 THEN
        PRINT
        PRINT "There are now a total of "; Ltotal! + L; " kg of loose"
        PRINT "sand per square metre of surface area"
        IF area > 1 THEN
                PRINT "for a total of "; (Ltotal! + L!) * area; " kg of
                        sand over the "; area; " square metre area."
        END IF
8180 END IF
8190 Ltotal! = Ltotal! + L!
```

```
8200 Lsum = Lsum + L!
8210 Lperiod = Lperiod + 1
8220 Lrun = Lrun + 1
8230 GOTO 2000 'completion screen
8240 REM wind > 6
8250 PRINT
8260 PRINT "During this 12-hour period, average wind speed exceeded the"
8270 PRINT "minimum threshold necessary for aeolian transport, and all"
8280 PRINT "loose sand was removed from the area."
8290 L! = L! * S 'dried layer no longer affects sand release
8300 PRINT
8310 PRINT L; " kg of sand per square metre were released from the "
8320 PRINT "surface by pore-ice sublimation."
8330 IF area > 1 THEN PRINT "for a total of "; L! * area; " kg over the ";
        area; " square metre area."
8340 IF Ltotal! = 0 THEN
                PRINT
                PRINT "All of the released sand was moved by wind."
        ELSE
                PRINT
                PRINT "There were already "; Ltotal!; " kg of loose sand"
                PRINT "per square metre on the surface; therefore "; L! +
                        Ltotal!; " kg"
                PRINT "per square metre were removed by the wind over the
                        12-hour period."
                IF area > 1 THEN
                        PRINT "for a total of "; (L! + Ltotal!) * area; "
                                kg over the "; area; " square metre area."
                        END IF
8350 END IF
8360 Qtotal! = Qtotal! + L! + Ltotal!
8370 Lsum = Lsum + L
8380 Ltotal! = 0
8390 Lrun = 0
8400 Lperiod = Lperiod + 1
8410 Qperiod = Qperiod + 1
8420 GOTO 2000 'completion screen

9000 CLS 0
9005 PRINT "********** Simulation Summary **********"
9010 PRINT
9020 PRINT "Total number of periods: "; n; "   Area:  "; area; "m2"
9030 PRINT
9040 PRINT "Conditions                               Number of Periods"
9050 PRINT
9060 PRINT "too warm                                ", warmperiod
9070 PRINT "possible melting at surface             ", meltperiod
9080 PRINT "ice-covered                             ", iceperiod
9090 PRINT "snow-covered                            ", snowperiod
9100 PRINT "unlimited loose sand but no movement", nperiod
9110 PRINT "sand released from frozen ground    ", Lperiod
9120 PRINT "sand moving                             ", Qperiod
9130 PRINT
9140 PRINT "Total sand released from frozen surface:  "; Lsum * area; "kg"
9150 PRINT
9160 PRINT "Total sand moved by wind: "; Qtotal! * area; "kg"
9170 PRINT
9180 PRINT "Loose sand remaining at end of simulation: "; Ltotal! * area; "kg"
9190 PRINT
9195 IF alpha = 2 THEN PRINT "Results (by time-period) have been placed in
```

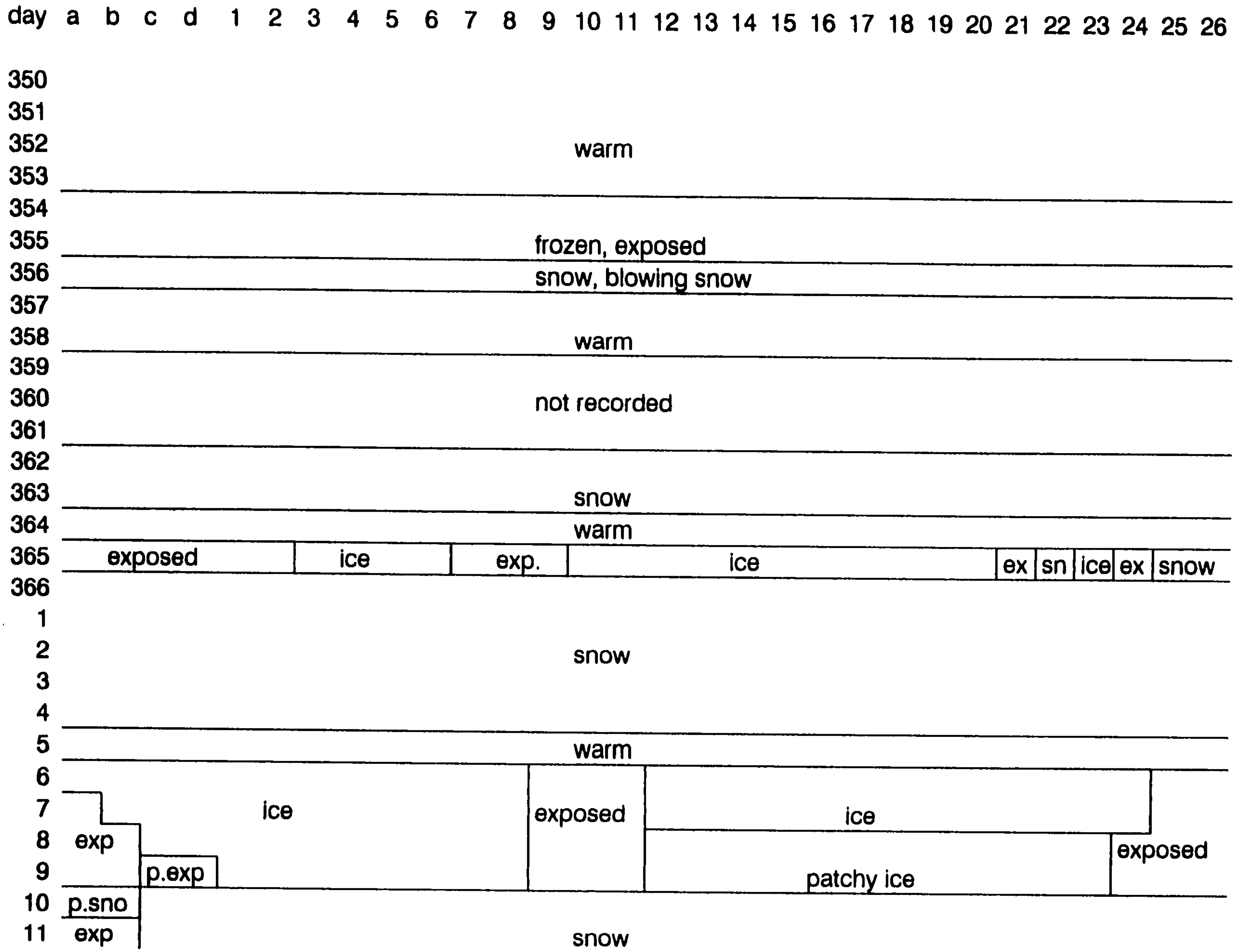
```
    the file: ", m$
9200 PRINT "******************************************"
9210 PRINT
9220 INPUT "Type 1 to start over, 2 to exit:  ", gamma
9230 IF gamma = 1 THEN GOTO 100
9240 IF gamma = 2 THEN 9900

9400 REM write results to file subroutine
9410 OPEN m$ FOR APPEND AS #2
9420 WRITE #2, label, n, warm, melt, ice, snow, nomove, sublim, L!, Ltotal!,
    Lsum, move, Q!, Qtotal!
9430 CLOSE #2
9440 warm = 0
9445 melt = 0
9450 ice = 0
9455 snow = 0
9460 nomove = 0
9465 move = 0
9470 sublim = 0
9480 RETURN

9500 REM wrong input prompt subroutine
9510 PRINT "I'm sorry, your entry is not recognized by this program."
9520 PRINT "Please check your options and try again."
9530 RETURN

9600 REM Ltotal! to zero when all sand is loose subroutine
9610 PRINT
9620 PRINT "Previously, ", Ltotal!, "kg of sand per square metre were released"
9630 PRINT "from the frozen surface by pore-ice sublimation.  All frozen sand"
9640 PRINT "is now uncemented and the amount of 'released' sand will not be"
9650 PRINT "saved for future calculations."
9660 Ltotal! = 0
9670 Lrun = 0
9680 RETURN

9700 REM Ltotal! to zero when snow, ice or warm periods occur
9710 PRINT
9720 PRINT "Previously, ", Ltotal!, " kg of sand per square metre were released"
9725 PRINT "from the frozen surface by pore-ice sublimation.  Snow, ice, and"
9730 PRINT "warm periods change the condition of the surface and can add"
9735 PRINT "moisture through vapour transfer, melting and refreezing, and rain."
9740 PRINT "The amount of 'released' sand will not be saved for future"
9745 PRINT "calculations."
9750 Ltotal! = 0
9760 Lrun = 0
9770 RETURN

9800 REM Ltotal! when direct entrainment occurs
9810 PRINT
9820 PRINT "Previously, ", Ltotal!, " kg of sand per square metre were released"
9830 PRINT "from the frozen surface by pore-ice sublimation.  This released"
9840 PRINT "sand will be entrained first and removed from the area."
9850 Ltotal! = Ltotal! - Q!
9860 IF Ltotal! < 0 THEN
    Ltotal! = 0
    Lrun = 0
9870 END IF
9880 RETURN
```

```
9900 PRINT
9910 PRINT "Thank you for your participation."
9920 END
```

APPENDIX D

Beach Surface Observations

A chart of beach surface conditions has been produced from daily observations of the study area on Presqu'ile Beach. Observations correspond to stakes extending across the width of the beach. Stake numbers appear at the top of the chart; stake 1 is closest to the icefoot and stake 26 is closest to the foredune (please refer to figure 4.2 on page 68 for stake locations). The stakes were spaced three metres apart. Observations were extended beyond the row of stakes to the edge of the icefoot, and letters a-d at the top of the chart denote three-metre intervals between stake 1 and the icefoot. The numbers in the left column of the chart indicate the date of observation (as a Julien Day). Observations, which may be abbreviated where space is constrained, include exposed frozen sand (exposed, exp. or ex), snowcover (snow or sn), surface ice (ice), thawed conditions (warm), surface water (water), and periods of no records. Where surface cover was not continuous in an area, patchy conditions are recorded (patchy or p.).


day
a
b
c
d
1
2
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4
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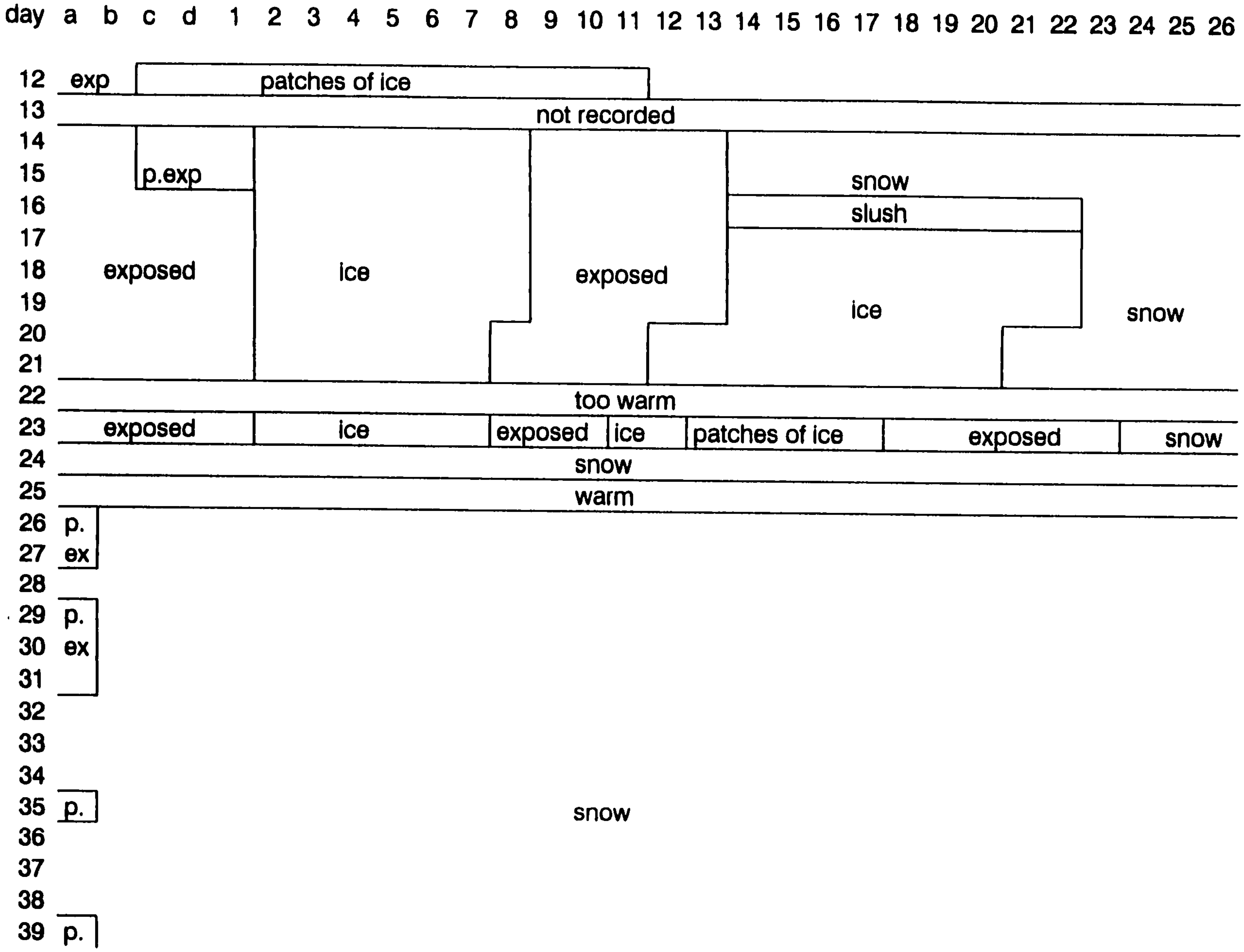
359
360
361
362
363
364
365
366
1
2
3
4
5
6
7
8
9
10
11
warm
frozen, exposed
snow, blowing snow
warm
not recorded
snow
warm
exposed
ice
exp.
ice
ex
sn
ice
ex
snow
snow
warm
ice
exposed
ice
exp
p.exp
patchy ice
exposed
p.sno
exp
snow


day
a
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15
16
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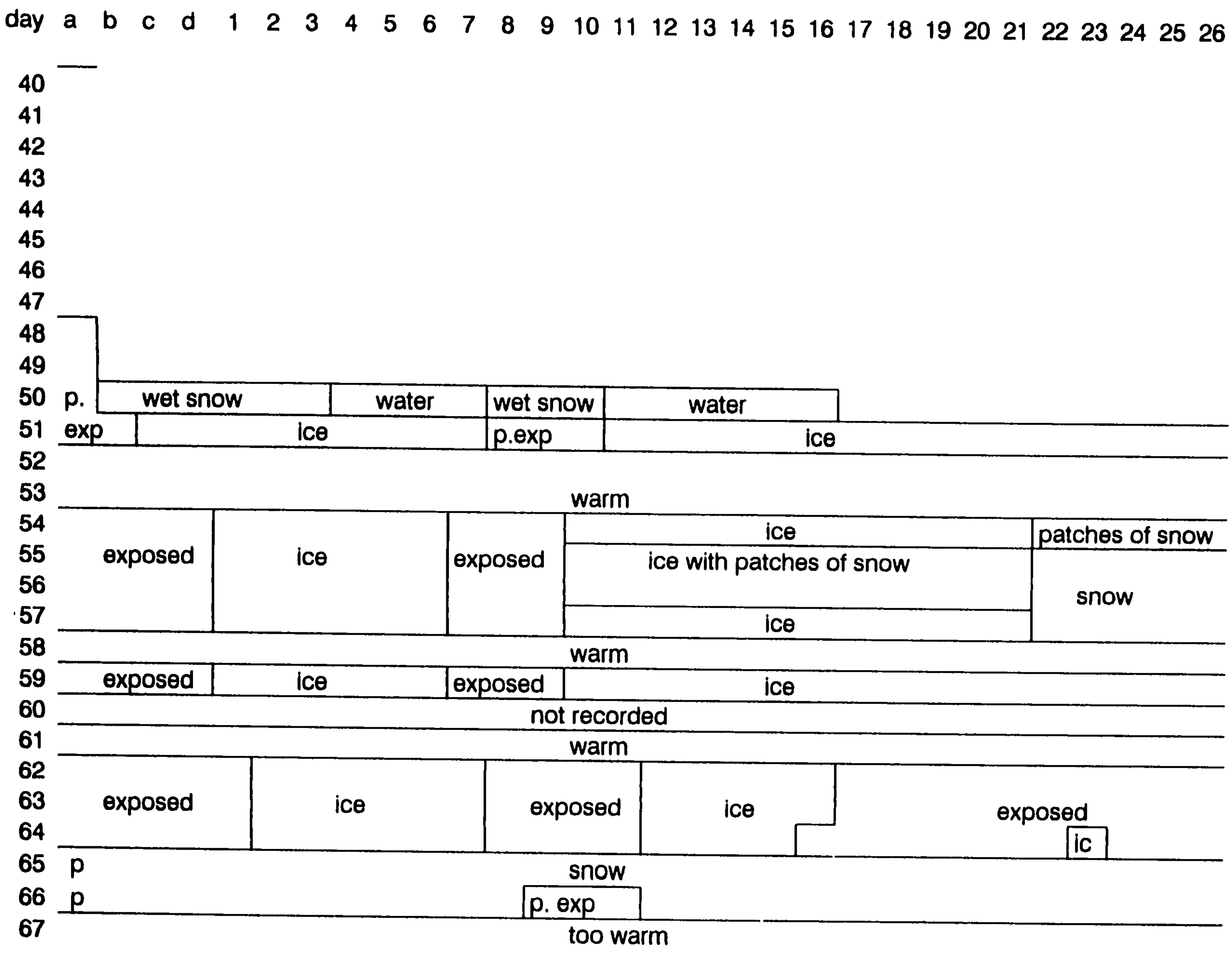
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
exp
patches of ice
not recorded
p.exp
exposed
ice
exposed
snow
slush
ice
snow
too warm
exposed
ice
exposed
ice
patches of ice
exposed
snow
snow
warm
p.
ex
p.
ex
p.
snow
p.


day
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62
63
64
65
66
67
p.
wet snow
water
wet snow
water
exp
ice
p.exp
ice
warm
exposed
ice
exposed
ice
patches of snow
ice with patches of snow
snow
ice
warm
exposed
ice
exposed
ice
not recorded
warm
exposed
ice
exposed
ice
exposed
ic
p
snow
p
p. exp
too warm

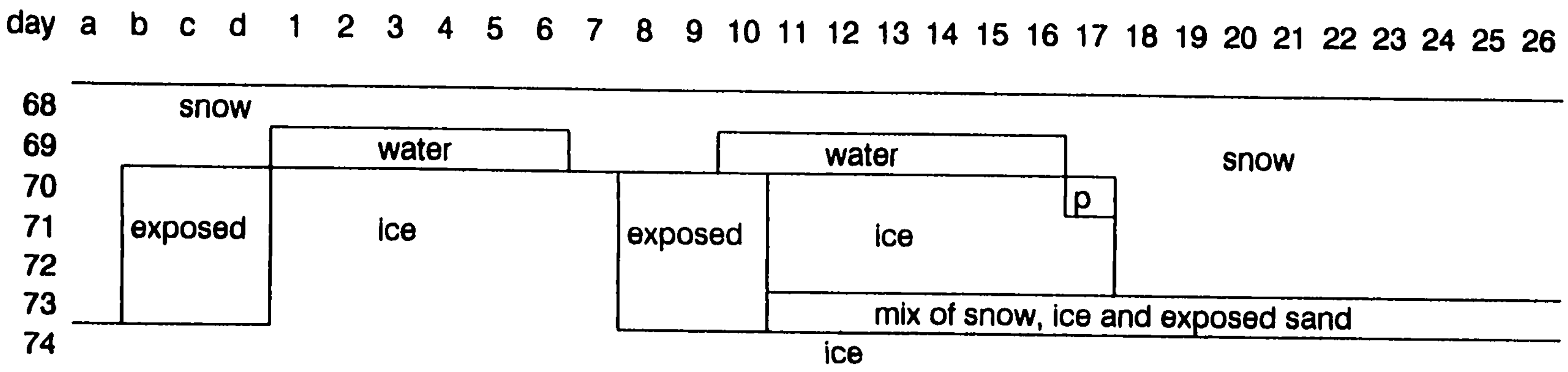
day
a
b
c
d
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
68
69
70
71
72
73
74
snow
water
water
snow
exposed
ice
exposed
ice
p
mix of snow, ice and exposed sand
ice

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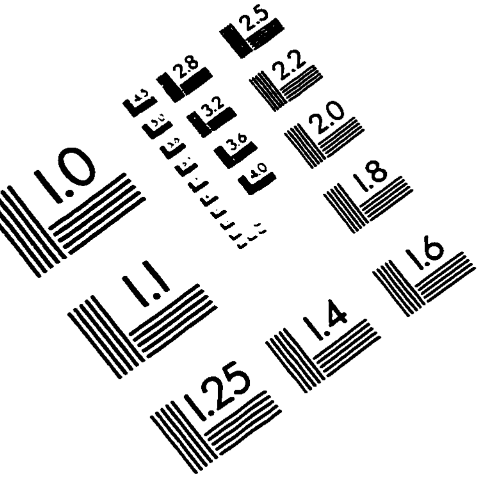
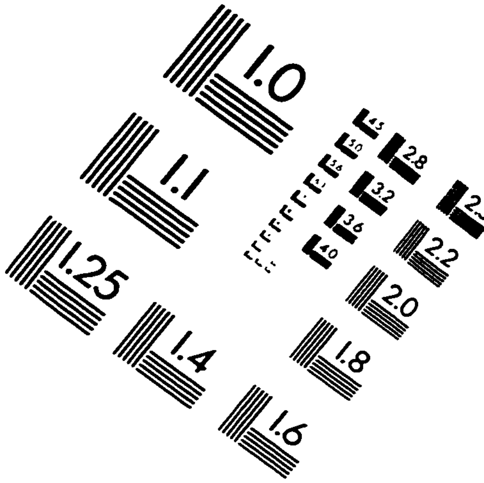
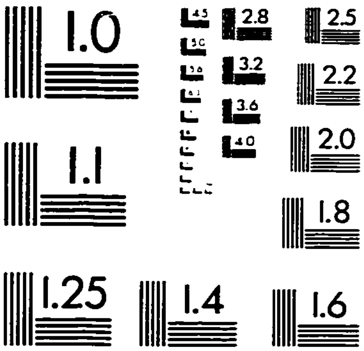
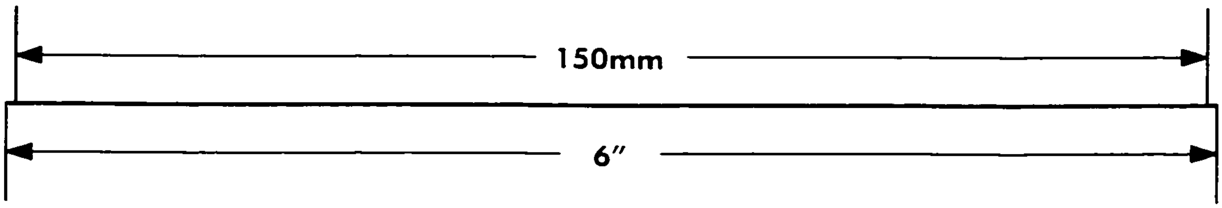
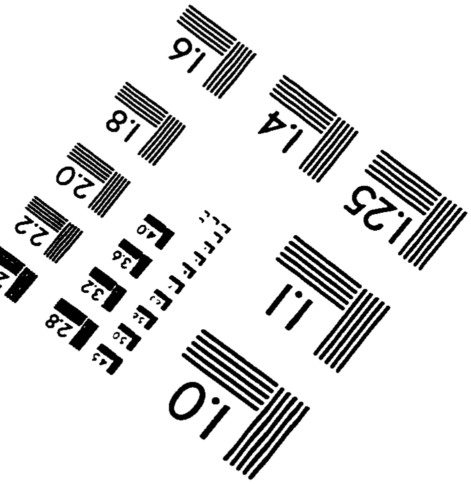
IMAGE EVALUATION TEST TARGET (QA-3)

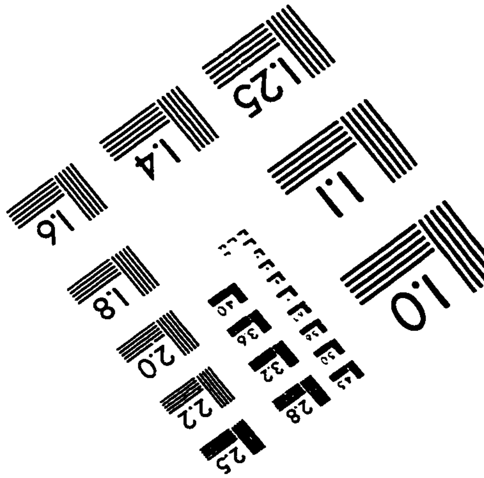












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