ECOLOGICAL-HUMAN MODELLING AND ENVIRONMENTAL ASSESSMENT
A LONG POINT, LAKE ERIE, CASE STUDY AND POLICY EVALUATION

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ABSTRACT

The purpose of this report is to develop and apply a conceptual framework of environmental stress-response for a geomorphic system. A review of theories and methodologies in ecology and geomorphology has provided a number of stress concepts pertinent to modelling environmental stress-response, including those related to stress-dependency, frequency-recovery relationships, environmental heterogeneity, spatial hierarchies and linkages, structural-functional response, and temporal change. Constructs and methods generated from the literature review are applied in the development of an integrative stress-response framework using existing environmental assessment techniques: interaction matrices and a systems diagram. The major emphasis of the framework is on the interaction between environmental stress and the geomorphic environment of the Long Point sandy barrier system. Findings of the model are applied in a discussion elaborating the stresses operating on several key barrier subsystems. This discussion indicates Long Point's stress-response and recovery are greatly impacted by fluctuating water levels, stress intensity and frequency, as well as environmental gradients such as differences in sediment storage and supply. Aspects of these stress-response variables may be articulated in terms of three main conceptual challenges to management: dynamic stability, spatial integrity, and temporal variability. These in turn form the framework for evaluative principles which are applied to assess how the policies and practices of Long Point Provincial Park reflect key biophysical processes and human stresses identified by the model.

RÉSUMÉ

Le but de ce rapport est de formuler et d'appliquer un cadre théorique de reponse au stress environnemental dans un système geomorphique. L'étude de theories et de methodologies en écologie et en géomorphologie nous a fourni certains concepts nous permettant de définir un modele de reponse au stress environnemental: dépendance sur le stress, fréquences de retablissement du stress, variabilité environnementale, hierarchies et liens spatiaux, réponses structurelles et changement temporel. Les concepts et méthodes empruntes à la recherche existante sont appliques à la mise au point d'un cadre general de reponse au stress qui fait appel à des techniques d'évaluation environnementale déjà existantes: matrices d'interaction et diagrammes de systèmes. Le cadre conceptuel met l'accent principal sur l'interaction entre le stress environnemental et l'environnement géomorphique du systeme de barre de sable de Long Point. Le modele est applique dans une discussion des stress affectant plusieurs sous-systèmes clés de la barre de sable. 11 ressort de la discussion que la reponse au stress et que le retablissement de Long Point subissent l'impact considerable de la fluctuation du niveau d'eau, de l'intensite et de la fréquence du stress, ainsi que de gradients environnementaux comme les differences d'offre et d'accumulation de sediments. Ces variables de reponse au stress peuvent être exprimees en fonction de trois enjeux théoriques principaux de gestion: stabilité dynamique, intégrité spatiale et variabilite dans le temps. Ces concepts forment à leur tour le cadre de principes servant à évaluer dans quelle mesure la politique et les pratiques du Parc Provincial de Long Point refletent les processus biophysiques clés et les facteurs humains de stress identifies par le modele.

1. INTRODUCTION

A. Theoretical Rationale of Research

Environmental management, in its most fundamental form, attempts to resolve the conflicts that arise from the interaction between human and natural systems. However, despite ongoing research and theorizing, knowledge about the 'interface' within and among environmental and human systems is still limited (Johnston 1983). For instance, environmental impact methodologies are still fettered by limited understanding of ecosystem structure and functioning, restricting their use in identifying system responses to human stresses (Beanlands and Duinker 1983). Bastedo *et al.* (1984) noted that common deficiencies in resource surveys include: tending to stress either biophysical or cultural information; failing to distinguish between ecologic processes and features; and failing to communicate information in a useful and/or easily comprehended framework. Environmental management is also hampered by inappropriate data, collected in a fragmented and piecemeal manner by agencies perhaps only narrowly connected with the problem at hand (Rapport and Friend 1979). The superabundance of information can also hamper effective environmental management, causing managers to be swamped with undigested environmental information often contributing little to understanding (Schaeffer *et al.* 1988) and even obscuring causes and solutions (Sokolik and Schaeffer 1986).

It is argued that understanding the determinants of natural system states and the agents causing stress or modification of the system are both necessary for proper management. Karr (1981) called for approaches which translate the often complex data on ecosystems into simple and understandable information about environmental conditions which can be used for decision making. Rapport and Friend (1979) suggested that such environmental data must yield information not only on the state of the environment, but also on the dynamic processes (stress forces) and dynamic stress response, including identification of instability thresholds and systems undergoing chronic or acute stress. However, the study of environmental stress has stayed primarily within disciplinary bounds, theoretical constructs and methodologies being developed unevenly and almost separately in ecology, environmental management, and geomorphology . Thus, while stress-response frameworks are well established in disciplines such as ecology, no methodological framework has been developed to guide the assessment and analysis of environmental stress-response in geomorphic environments, despite widely apparent human impact on such environments (Goudie 1981; Nir 1981).

The theoretical basis of modelling interactive ecological-human systems needs to be advanced through the development of integrative terminology and methodologies that identify key components and processes in stress-response systems. Existing nomenclature and methodologies from ecology and geomorphology need to be assessed as to their suitability in identifying and integrating those components and processes that help determine regional and ecosystem stress-response. Ecological and systems theory may be particularly helpful in developing a conceptual framework which identifies key components and processes in an interactive ecological-human context. This stress-response framework can then be used to assess environmental management policies. The interactive ecological-human model to be modelled is the Great Lakes' sandy barrier.

The multitude of confusing and often contradictory stress terms have been discussed elsewhere (e.g. Barret 1981; Rapport et al. 1985). To avoid misinterpretation, the terms stress, perturbation, and disturbance will be used synonymously in this paper to mean some agent or action that causes a system reaction (structural of functional) beyond that attributable to average natural background conditions. Response will refer to a change in system structure or dynamics in reaction to a stress.

B. Practical Rationale of Research

Ontario's 9,800 km of Great Lakes' shoreline are a significant multiple-use resource. Small but important components of this resource are its sandy barriers. These depositional features range from small stream mouth barrier beaches to the world's largest freshwater sandspit, Lake Erie's Long Point. Built by longshore sediment transport and deposition, sandy barriers are low-lying, beach-dune complexes, often protecting the mainland and adjacent wetlands, marshes, estuaries, and/or bays from the direct force of wave and storm energy. Sandy barriers are acknowledged to be highly sensitive, complex, interactive, ecological and geomorphological systems, supporting significant habitats for fish and wildlife as well as a wide variety of human activities. Yet, the often intensive public and private uses and developments have not respected the dynamic nature of shore processes and fluctuating lake levels which influence the long-term maintenance and evolution of barrier systems. For example, while Long Point has been designated a United Nations biosphere reserve, it continues to be pressured by development proposals (Kitchener-Waterloo Record 1991; Mentek 199 1).

Periods of high lake levels and dramatic storms are generally times of upheaval on sandy barriers. Evidence of short-term stress includes flooding of low-lying areas, cliffing of dunes, and apparent loss of beaches and wetlands. However, the biotic and physical components of Great Lakes' sandy barriers, such as dune and wetland vegetation or the barrier beaches themselves, have evolved over time in response to the interaction of many interdependent biophysical processes, including water level fluctuations, sediment budgets, and climatic forces. While these processes are important to the dynamic stability of sandy barrier resources, they also influence the long-term development and evolution of sandy barriers.

The dynamic interrelationships between natural processes such as inlet and overwash dynamics and responses of beaches, dunes, marshes, and vegetation have been examined by numerous researchers (e.g. Dolan 1973; Godfrey 1977; Leatherman 1979). In addition, many studies have evaluated the effect of environmental stress, with an emphasis on investigating responses to unusual, external or low probability stresses to which an ecosystem is not preadapted. Generally, such studies use either a site-specific or mono-stress approach, focusing on the negative effects of "sledge hammer blows" (Schindler 1987) like hurricanes (Fink1 and Pilkey 1991) or human stresses such as shoreline modification (e.g. Dolan 1976; Everts 1980; Nordstrom 1987). Human stresses can be divided into two general categories: activities which intend to modify barrier processes and structures directly (e.g. coastal engineering); and other activities which have incidental, though significant, effects (e.g. residential development) (Meisburger *et al.* 1980).

However, site-specific approaches fail to recognize that: 1) the effects of a perturbation may vary significantly at differing locations; 2) stresses detrimental at one level can be beneficial at higher levels; or 3) that stresses may have sometimes produce both positive and negative effects at the same ecosystem level. Mono-stress approaches ignore the cumulative and interactive nature of both human and natural stresses. For example, the simultaneous occurrence of two or more stresses may render each more significant than if each stress was acting alone **(synergism).** Likewise, simultaneous occurrence might render stresses less effective **(antagonism).** However, few methodologies have been developed to account for such variants in stress-response relationships.

There is a need to better appreciate these various biophysical processes and related human and natural stresses in a holistic fashion, in an effort to understand the sensitive, evolutionary, and dynamic character of sandy barrier systems. While work by Francis ***et al.*** (1985) and Knight (1983) has primarily attempted to model biotic systems and stresses at Long Point, this project proposes to concentrate on modelling the geomorphic system, the critical land base for all ecological processes.

C. Purpose and Objectives

The purpose of this report is to develop and apply a conceptual framework of environmental stress-response for a geomorphic system. The main objectives are:

- to review various theories and methodologies used to analyze environmental stress, with a focus on identifying constructs and methodologies which are useful for conceptualizing environmental response to both natural and human stresses;

- to use the constructs and methods generated from the literature review to guide the development of a ecological-human model which can help describe and analyze environmental stress-response in a specific geomorphic system, the sandy barrier;

- to apply the sandy barrier model in a case study of Long Point, a Great Lakes' sandy barrier which typifies a regional geomorphic landform stressed by a wide variety of human pressures and natural processes; and

- to use the conceptual model to develop evaluation criteria or management principles to assess how management policies and practices reflect the key biophysical processes and human stresses identified by the ecological-human model; and

- to apply the evaluation criteria to the policies and practices of a selected Long Point management agency, the Long Point Provincial Park.

2. CONCEPTUALIZING ENVIRONMENTAL STRESS-RESPONSE

Advances in conceptualizing environmental stress-response complexities have been evident in ecology (e.g. Odum *et al.* 1979), including stress ecology (e.g. Barret 1981), patch dynamics (e.g. Pickett and White 1985), and landscape ecology (e.g. Mooney and Godron 1983), and in geomorphology (e.g. Brunsden and Thornes 1979). Those most pertinent to this study, and arguably any stress-response model, include the concepts of stress-dependency, stress frequency and recovery, environmental heterogeneity, spatial hierarchies and linkages, structural-functional response, and temporal change.

A. Stress-Dependency

Several researchers have recognized that not all stresses adversely impact ecosystem viability, and that environmental systems may actually require certain types of anticipated, repetitive stress for their persistence (e.g. Vogl 1980). Within geomorphology , stress is considered as the driving force behind all geomorphic processes, and thus helps develop and maintain geomorphic systems (e.g. Strahler 1952). Odum *et al.* (1979) made a useful distinction between **stresses,** perturbations that are unfavourable to ecosystem performance, and **subsidies,** perturbations that improve the overall functioning of an ecosystem. Furthermore, the authors suggest that system stress response may actually follow a **subsidy-stress gradient** where low level perturbations may enhance system functions and structures, but cause degradation at higher levels. Similarly, Rapport *et al.* (1985) adapted the stress terminology of Seyle (1956) to classify stress at ecosystem levels. Seyle termed stresses which act to the advantage of long-term self-regulatory processes as **eustresses. These are** distinct from stresses that adversely impact system viability, which are classified as **distresses.**

B. Stress Frequency-Recovery

While stress-dependent systems may have quick recovery rates, system stability and recovery is dependent on a normal range of intensities, frequencies and magnitudes. Often, the severity of an impact is augmented if the time between perturbations is decreased or increased. In the former case, increased frequencies do not allow full recovery. In the latter case, stresses occur too infrequently to allow system adaptation to occur. Such distinctions are evident in Whittaker’s (1974) **cataclimax concept,** as well as distinctions between **disasters-catastrophes** (Harper 1977) and **pulse inputs-general stress** (Vogl 1980).

Many stress-related concepts in geomorphology emphasize the importance of stress frequency for system response and recovery, including **magnitude-frequency** concepts such as **geomorphic effectiveness** (Wolman and Gerson 1978) and those related to **relaxation time (e.g.** characteristic-form time; transient-form ratios) (e.g. Allen 1974; Thornes and Brunsden 1977). Relaxation time is commonly interpreted as the period of adjustment after a geomorphic threshold is exceeded, or the time a system requires to achieve a new equilibrium by adjusting to the new conditions (Thornes and Brunsden 1977). The duration between a stress and its response, when the system absorbs the disruption, is termed **reaction time** (Renwick 1992). **Total response time** refers to the sum of relaxation and reaction time

(Renwick 1992). Stability can only be achieved if total response time is shorter than the interval between stress events.

Brunsden and Thornes' (1979) concept of **pulsed-ramped inputs** also recognizes the importance of stress frequency for stress-response, while recognizing such response also depends on stress types (e.g. human-natural), environmental conditions and spatial scale. **Pulsed inputs** refer to inputs of short duration, usually typical of extreme, episodic events, after which the system generally returns to, or near to, the pre-stress state. The authors noted that stress-response to such events depends on: 1) differences in climatic conditions and the relative efficiency of more frequent events; 2) the uniqueness of result relative to response to more frequent events; and 3) the degree of variability in extreme events, where large variations tend to cause landscapes dominated by large events, and abrupt discontinuities, scars, and variations in relief. System response is generally spatially and temporally restricted. **Ramp inputs are** sustained at the new level once initiated, normally the result of permanent shifts in controlling variables or boundary conditions (e.g. changes in climate, vegetation, land-use, or base level). Such inputs may cause a shift in process domains, and can be applied over a wide area, yielding uniform spatial response.

C. Environmental Heterogeneity

Both ecology and geomorphology recognize the importance of environmental heterogeneity for stress-response. Within ecology, environmental heterogeneity is discussed in terms of **environmental gradients (e.g.** Cowles 1899) and **climax pattern succession** (Whittaker 1953). Patch dynamics and landscape ecology recognize the importance of environmental heterogeneity and stress regimes in producing ecological mosaics (landscapes) comprised of several ecosystems (i.e. patches, ecotypes, landscape cells). Both recognize the contributions of environmental heterogeneity to differing stress susceptibilities and variabilities in stress-response. The basic premise is that most perturbations produce heterogenous patches, responses, and recoveries that are strongly dependent on the biotic and abiotic characteristics of pre-disturbance environments. The environmental heterogeneity of stress-response has been similarly discussed in geomorphology using the concept of **dominance domains** (Kirkby 1980; Thornes 1983). This concept recognizes that the dominance of geomorphic processes varies spatially according to often intersecting environmental gradients (e.g. rainfall intensity, cover density).

Environmental heterogeneity is also linked to system stability through ecological concepts such as **shifting mosaic steady-state** (Bormann and Likens 1979) and **patch dynamics** (Pickett and White 1985). These concepts consider ecosystems as arrays of irregular patches composed of components with different characteristics (e.g. ages, productivity) that result from localized disturbances and different micro-environments. However, the resulting differences in patch production and respiration balance one another in steady-state landscapes characterized by constant recycling by randomized local stresses which eventually cover a whole ecosystem.

D. Spatial Hierarchies

Concepts like flexible strategies (Koestler 1978), stress incorporation (O'Neill et *al.* 1986), and system degeneration-regeneration (Allen and Starr 1982; O'Neill *et al.* 1986) recognize that ecological stress-response is dependent on hierarchical levels, interactions, and buffers. Generally, these concepts regard each hierarchical level as a filter, altering signals to lower frequencies as they pass up through a hierarchy (O'Neill *et al.* 1986). Perturbations are considered intrusive, uncontrolled external events out of tune with the local behaviour frequencies of the disturbed holons (hierarchical levels) (Allen and Starr 1982; O'Neill *et al.* 1986). Higher levels are relatively buffered from perturbations occurring at lower levels, as they only "see" the averaged or integrated responses of lower levels. Thus, higher levels can affect lower-level holons but are relatively unresponsive to changes at lower levels (O'Neill *et al.* 1986). However, if perturbations occur at higher scales, they eliminate lower-level components unable to resist the disturbance. In addition, stresses beyond threshold conditions can break hierarchies down to the levels of the largest stable sub-system, or result in hierarchical restructuring (Allen and Starr 1982; Haigh 1987). Generally, instability occurs when stress levels cause lower level reaction times that are too fast for the self-regulating system of the perturbed holon, thereby tearing the system apart.

Several geomorphologists have suggested that system controls and stress-response may be scale dependent (e.g. Renwick 1992; Thornes and Brunsden 1977). Haigh (1987) suggested that geomorphic thresholds are often the response to signals moving through the various levels of an holarchy. Campbell and Honsacker (1982) proposed the existence of a graded continuum of thresholds in which the cumulative effects of thresholds at smaller scales (e.g. slopes) are felt at higher levels (i.e. landscape). Trofimov and Phillips (1992) suggested that stability and instability may be associated with different hierarchical levels, where instability at one level is compensated by accelerated structural development and abrupt spatial broadening at higher organizational levels. Instability broadens system opportunities by increasing the number of ways a system can change to a new level of organization. Increases in stability of developing geomorphic systems obstruct changes to new organization levels, while development processes are better explained by instability.

E. Spatial Linkages

Implicit in the concept of spatial hierarchies is the concept of spatial linkages. Both ecology and geomorphology recognize the importance of spatial linkages for stress-response, including the types of ecosystems 'upstream' and the transfers of materials and energy between adjacent systems. Spatial linkages are particularly stressed within landscape ecology, including both corridors (e.g. Formon and Godron 1981) and ecotones (e.g. Forman and Moore 1992), though are also recognized by geomorphic concepts such as sediment budget modelling (e.g. Rawat 1987), and the catena concept (e.g. Schiedegger 1986)).

Spatial linkages may help provide system stability, as increased redundancy in functional linkages provide alternative pathways for carrying out critical functions. For example, Gardner *et al.* (1987) suggested that habitat fragmentation may not have any effect until critical connective pathways are disrupted. Path density and strength of coupling between system components may also affect geomorphic stress-response (Brunsden and Thornes 1979). Higher path densities result in effects being rapidly and ubiquitously propagated. Mobile, fast responding subsystems have a high sensitivity to external stresses, with quick reaction and relaxation times. These components are relatively sensitive to climatic variation, and act as energy filters, passing only minor changes to contiguous subsystems. In addition, areas dominated by such components are morphologically complex, reflecting sensitivity to stress (transient forms), as well as rapid restorative capabilities (characteristic forms). Conversely, slowly responding, insensitive areas are characterized by low path densities and limited flows of energy, water and materials.

F. Structural-Functional Response

Both ecology and geomorphology distinguish between structural and functional stress-response. In ecology, both landscape ecology (e.g. Formon and Godron 1981) and ecosystem health (e.g. Schaeffer *et al.* 1988) have developed a number of structural and functional indicators of stress-response. In geomorphology , structural-functional response is generally considered in terms of complex response and feedbacks. Complex response (Schumm 1975) refers to landscape evolution where erosion cycles are characterized by episodes of erosion separated by periods of deposition and relative stability. Consideration of feedbacks are crucial to stress-response modelling. In geomorphology , such consideration generally involves comparing the relative predominance of stabilizing negative feedbacks and destabilizing positive feedbacks (Brunsden and Thornes 1979), and are often are considered in terms of sediment yield responses (e.g. erosion-deposition cycles).

Stability and stress-recovery may also relate to system storages. O'Neill and Reichle (1980) suggested using storage capability to identify system stability. Storage capability provides reserve supplies of energy or matter when producers are disrupted by environmental extremes, and are improved by large reserves that exhibit slow response times so that short-term environmental fluctuations have minimal effects. Formon and Godron (1986) argued that landscape stability may depend on the availability of biomass in a system. Bormann and Likens (1979) also discussed the important role of energy and nutrient storages in helping system repair following a perturbation, adding that increased storage efficiency helps speed system recovery. Similarly, Brunsden and Thornes (1979) noted that geomorphic areas with high storage capacities and limited transfers are relatively insensitive to external stresses.

G. Temporal Change

Conceptualization of stress-response must also recognize the issue of temporal change, both in stress regimes and environmental heterogeneity. In ecology, temporal change is generally considered in terms of succession and evolution (MacMahon 1980). Landscape ecology has stressed the importance of landscape change for establishing stress regime histories and trends (e.g. Delcourt and Delcourt 1992). Temporal change is also recognized through geomorphic concepts such as denudation chronology (e.g. Brunsden and Thornes 1979).

3. THE STUDY AREA

The Long Point sandy barrier is located on the north shore of Lake Erie, extending 41 km eastward from the mainland into approximately 60 m of water (Fig. 1). It forms a sink for glacial and glaciolfluvial sediments eroding from bluffs in a littoral cell that extends approximately 95 km westward. Bluff recession averages approximately 0.6 - 2.0 m per year for most of the cell, contributing approximately one million m^3 of sand per year to the spit (Rukavina and Zeman 1987). The spit has developed over the last 4000 years as a result of variations in longshore sediment transport, distal end deposition, and changing wave climates (Coakley 1983), and is presently growing lakeward at 4-7 m per year.

Several authors have divided the barrier into proximal, central, and distal zones, based on sediment budgets and morphology (e.g. Davidson-Arnott and Fisher 1992). The proximal and central zones are characterized by a negative sediment budget, leading to a transgressive shoreline of narrow beaches. Conversely, the distal zone has a positive sediment budget, and is characterized by wide beaches and embryo dune zones, more longshore sandwaves, and a prograding dune system.

Like similar systems worldwide, Long Point is a good example of a dynamically stable ecosystem, capable of adjusting to various stresses such as storms and fluctuating water levels. The barrier is in constant flux, characterized by continual changes in beach and dune profiles, as well as formation of new inlets and washovers during storm events. Many barrier processes are impacted by fluctuations in lake levels which occur on 3 distinct temporal scales: long-term (over several years, decades, or centuries), seasonal, and short-term (hours to days) (Blust 1978). Long-term fluctuations, responding primarily to differences in evaporation and precipitation, can vary up to 1 to 1.5 m. Seasonal fluctuations vary from 0.3 to 0.6 m, representing differences in precipitation and runoff, and typically peaking in June or July after the spring melt. In the short-term, storm seiches, surges, and waves can increase static levels up to 2.5 m in a few hours. A combination of short-term increases in water levels with record high long-term levels can increase high wave stress dramatically, as occurred on Lake Erie on December 2, 1985.

4. THE LONG POINT ECOLOGICAL-HUMAN STRESS-RESPONSE MODEL

Many conceptual modelling techniques have been developed to model environmental interactions, including checklists, spatial overlays, interaction matrices, and systems diagrams. While all the techniques help synthesize and summarize large amounts of information, they do differ in their ability to depict interactions between the human and physical environments, evaluate the impacts (indirect and direct) of those interactions, as well as communicate those interactions (Gilliland and Risser 1977; Lee 1983; Rosenberg *et al.*, 1981). Similarly, each type of model is restricted in its ability to incorporate approaches to modelling stress-response complexities. The choice of model for this study was dependent

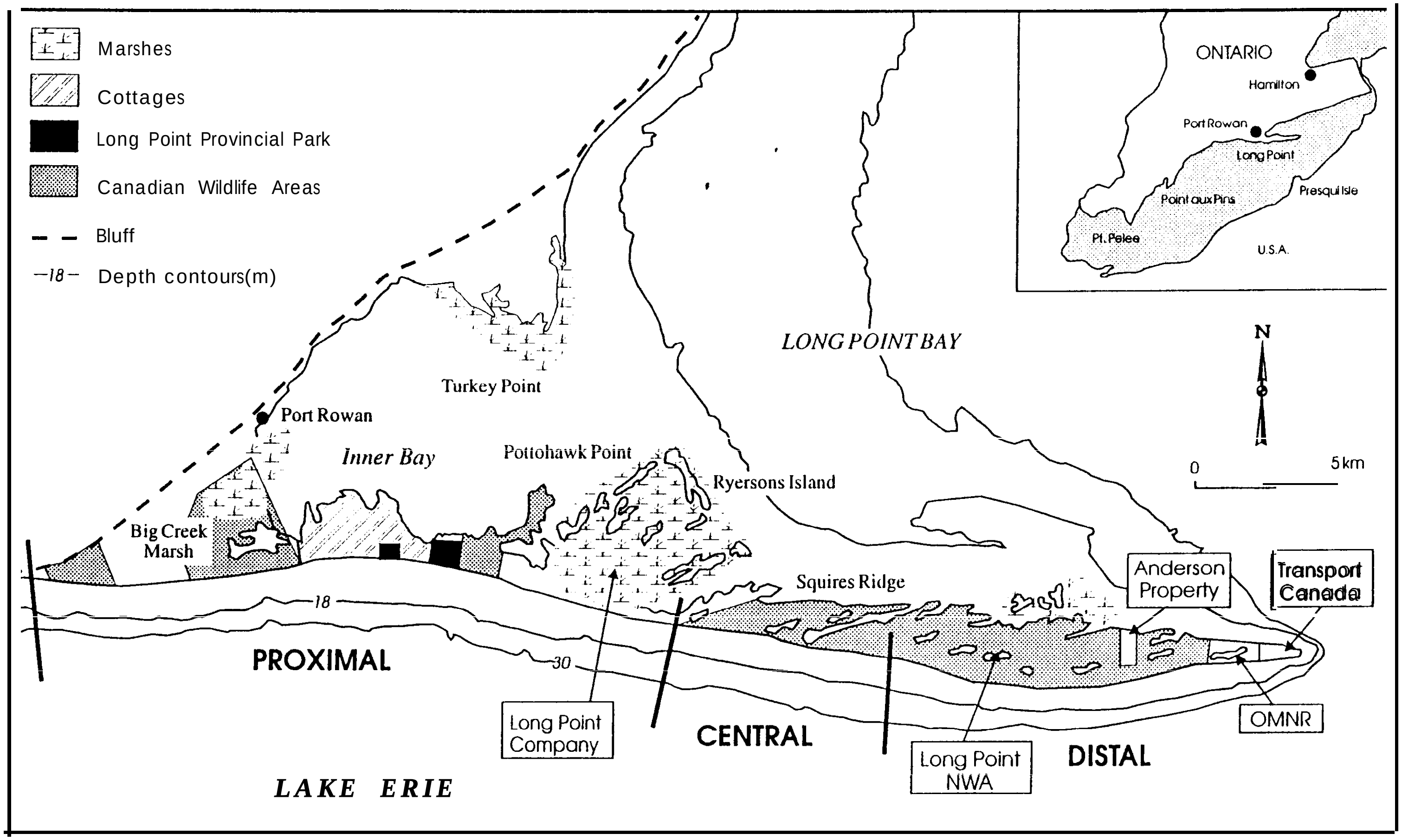

Fig. 1 The Long Point Sandy Barrier

on several criteria, including the ability to:

- make a number of dichotomous distinctions regarding stress types (human-natural; eustress-distress);
- show structural-functional relationships, especially storages, linkages, and feedbacks;
- address hierarchical concerns;
- limit system fragmentation;
- recognize the role of environmental heterogeneity; and
- accommodate issues of temporal change.

As no modelling technique is a panacea, this study combines several techniques into a hybrid approach similar to Knight (1983) and the ecological characterizations used by the U.S. Fish and Wildlife Service (Barclay 1978). This study's hybrid conceptual model combines use of interaction matrices and systems diagrams to provide information on the interaction between the various biophysical sandy barrier processes and stresses, identify key processes and components of sandy barrier systems, as well as indicate both the direct and indirect impacts of various human uses.

A. Stress Identification

The identification of stresses in a given area is usually somewhat arbitrary, based on ***a priori*** knowledge that such stresses are indeed operating in a system, and have a significant impact (Rapport and Friend 1979). Literature representing various biophysical, human use, and management scenarios was researched to identify the key biophysical processes and stresses contributing to the dynamic stability, spatial integrity, and temporal change of sandy barriers. The literature used included both scientific research of Great Lakes' sandy barriers (e.g. Fisher 1986; Saunders 1990; Conliffe-Reid 1991), as well as of barrier systems worldwide (e.g. Leatherman 1979; Oertel and Leatherman, 1985). Historical accounts and maps, research papers, newspaper articles, and aerial photographs were also key information sources (e.g. Bat-ret 1977; Cooper 1980; Knister 1931; Laidler 1944)). An effort was made to indicate the uniqueness of Great Lakes' barriers in comparison to other barrier systems worldwide, with emphasis on the effect of lake level fluctuations on biophysical processes and environmental stress.

Interaction matrices, a common methodology for cross-referencing common environmental stresses with environmental components, were used to compare barrier system components and processes with natural stresses and environmental uses in order to identify possible eustresses and distresses.

B. Barrier System Diagram

As interaction matrices fail to deal explicitly with spatial dimensions and give a fragmented view of environmental systems, a systems diagram, a common type of flow diagram used in modelling the dynamic nature of ecological-human relationships, was used to describe the structure and processes of a barrier system, identifying the key processes and components that may be affected by stress (Fig. **2)**

The systems modelling process began by building a compartmental flow diagram. Borrowed from systems science, this type of diagram is often used to make preliminary analyses of ecosystems. All entities in a system are represented as compartments, and interactions or fluxes among them are represented by arrows. In this study's model, the compartments are barrier sub-environments having some functional relationship to the barrier system. Several major sub-systems are regularly identified in the literature (e.g. Leatherman 1979). Flow arrows were used to represent sediment transfers among barrier subsystems. The greatest utility of this technique was its ability to describe and portray a hierarchy of interactions, including indirect relationships and feedbacks. In addition, the systems diagram proved to be a valuable organizational, evaluative, and communicative tool, particularity in conceptualizing an environmental system in its entirety.

Compartmental flow diagrams lack indication of the mechanisms underlying transfers between compartments, thus restricting the ability to understand how a system behaves under perturbations. Stress was represented using a signed digraph model, commonly used to denote positive and negative interactions between system components with different line symbols representing different causal effects (Jorgensen 1986). Causal arrows within this framework are qualitatively distinguished on the basis of "distresses" and "eustresses". The stresses or agents identified by the literature as influencing barrier processes were also divided into natural and human classes (Table 1).

5. SUMMARY OF SUBSYSTEM STRESS-RESPONSES

The model demonstrates that barrier subsystems and linkages are affected by different stresses. The following section applies findings of the model in a discussion elaborating the stresses operating on several key barrier subsystems, including beach/sandwave and dune/barrier flat subsystems.

A. Beach and Sandwave Subsystems

During extreme storm conditions, or a series of more moderate storms, large scale beach erosion can occur rapidly as subaerial sand is moved offshore to form surfzone bars (Thorn and Hall 1991). This sediment is generally returned onshore in an accretionary phase during low wave energy conditions. Thorn and Hall (1991) demonstrated that beach accretion is generally a much slower process than beach erosion, though recovery is initially more rapid and of a greater magnitude when beachface erosion is the most severe.

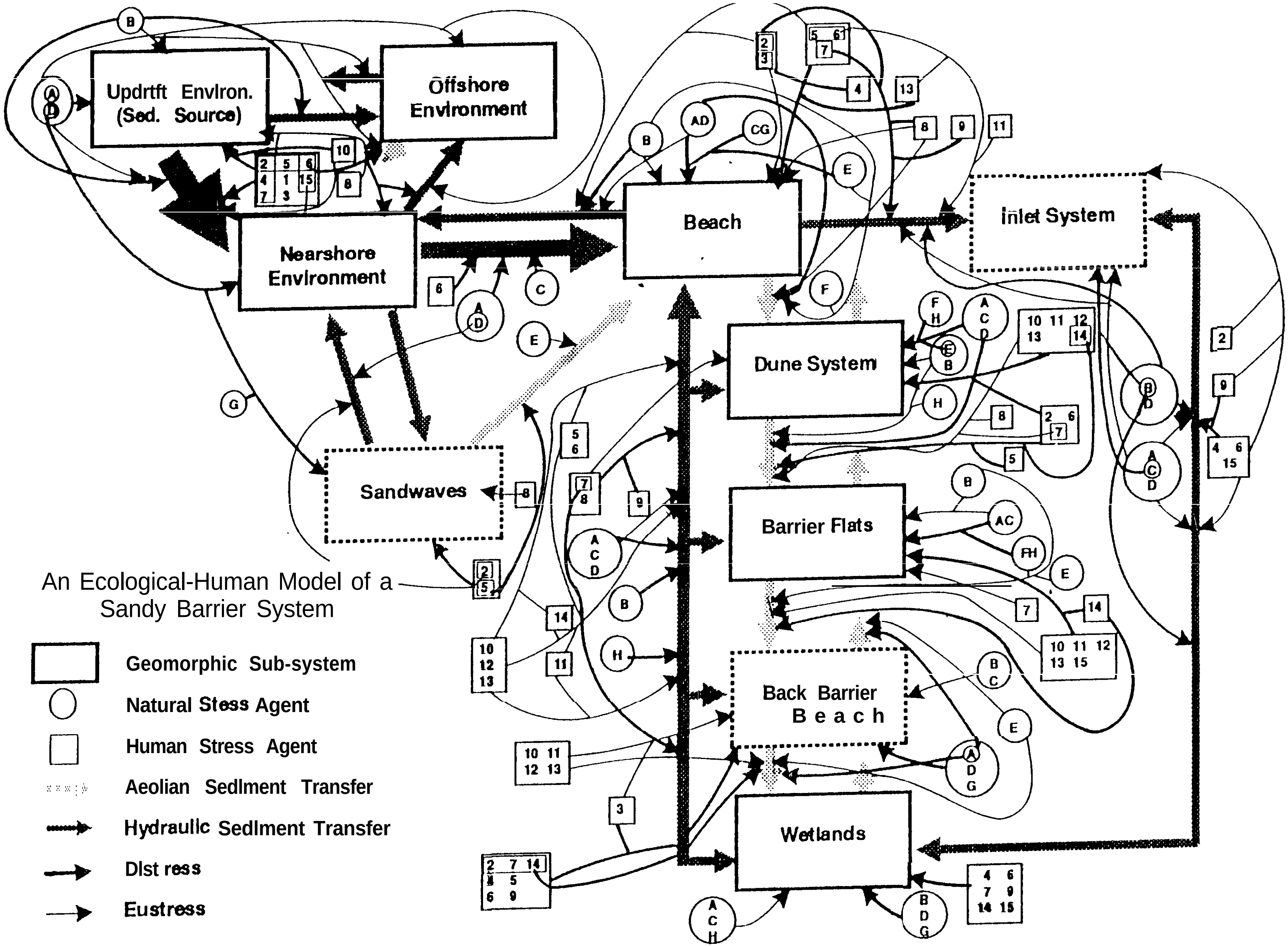

Fig. 2 The Long Point Model

Table 1
Barrier Stress and Responses

	Principal Distress	Principal Eustress
NATURAL STRESSES		
A. High Water	increased erosion	increased sediment supply
B. Low Water	decreased sediment supply	increased aeolian transfer, decreased erosion
C. Storm Surge	erosion, washovers, inlets	increased washovers, inlets
D. High Energy Waves	increased erosion, washovers	increased sediment supply, washovers, inlets
E. High Winds	blowouts	increased aeolian activity (absence of high water)
F. Drought	loss of vegetation	increased aeolian activity, wetland rejuvenation
G. Ice Scouring	increased erosion	protection of beach during winter storms
H. Fire	loss of vegetation	rejuvenation of wetlands
HUMAN STRESSES		
1. Dams	limit sediment supply	
2. Armouring	limit sediment supply, scour	possible site-specific decrease in erosion
3. Sand Traps	limit longshore drift	possible site-specific increase in sediment storage
4. Marinas/Jetties	limit longshore drift	site-specific protection of inlet entrance
5. Sand Mining	limit sediment supply steepen nearshore profile	
6. Dredging	limit sediment supply steepen nearshore profile	
7. Dune Building	limit overwash limit longshore drift	site-specific increase in sediment storage
8. Beach Nourishment		possible increase in sediment supply, longshore drift, and storage
9. Diking	limit overwash and wetland possible increased scour	
10. Vegetation Removal	dune destabilization slower stress recovery	
11. Lumbering	dune destabilization	
12. Grazing	dune destabilization	
13. Traffic	dune destabilization possible inlet formation slower stress recovery	
14. Residential/Park	dune destabilization	
15. Drainage	decreased sediment supply wetland impacts	increased sediment supply increase aeolian activity (lower water table)

Long Point's beaches respond to changes in wave energy, lake level, and sediment supply (Davidson-Arnott 1988). Higher wave energies and water levels associated with storm activity result in erosion of the beach and berm, causing beach flattening and the transport of sediment offshore. During calmer periods, the offshore sediment is returned onshore, either through the onshore migration of inner nearshore bars (Stewart and Davidson-Arnott 1988), or through a gradual build up of the berm. As storm frequency and intensity at Long Point are greatest in the spring and fall, beach profiles are generally much flatter in those seasons than in the summer months, allowing waves to reach much higher up the profile. Erosional effects of intense fall and occasional summer storms are reduced by the seasonally lower water levels and the initially wider beaches protecting the backshore. However, the seasonally high lake levels, narrow beaches, and storms of spring can lead to erosion of the backshore.

Sediment abundance in the shore zone influences beach geometry (width and height) and stress-response. Formed as nearshore bars weld onto the beach, longshore sandwaves widen beaches, further protecting dunes from erosion and over-wash, as well as acting as a control on dune sediment supply (Stewart and Davidson-Arnott 1988). Longshore sandwaves were found to help protect the shore at Long Point from over-wash and inlet formation, even during a severe storm on December 2, 1985 that resulted in widespread damage elsewhere on the barrier. Longshore sandwaves act both as a source and trap for windblown sediment in the late summer, leading to the development of embryo dunes and an extensive foredune ridge, which are later eroded as the longshore wave continues to migrate (Stewart and Davidson-Arnott 1988).

Periods of record high lake levels often result in narrower beaches as a new equilibrium profile is established (Olson 1958). The lag time between rising water levels, and the onshore migration of bars and replenishment of beach sediment, may also reduce the effectiveness of the migrating bars and narrow beaches in absorbing storm wave energy (Hands 1983). The narrow beach widths associated with high water periods also reduce the size of source area for aeolian transport, restricting dune growth.

The negative impacts of shoreline engineering projects on the dynamic equilibrium of barrier beaches have been investigated by various researchers (e.g. Dolan 1976; Everts 1980; Leatherman *et al.* 1978; Nordstrom 1987; Pilkey *et al.* 1980). Updrift seawalls and groins can cause sediment deficits downdrift, leading to narrower beaches, increased over-wash, dune cliffing, and inlet formation (Leatherman *et al.* 1978). Loss of beach width may be accelerated by seawalls as waves attacking the beach rebound off the breakwater and carry sand offshore, gradually narrowing the beach (Dolan 1976; Pilkey *et al.* 1980) as well as hampering post-storm recovery (e.g. Nelson 1991). As on a reflective beach, high wave energy is concentrated in an increasingly restricted run-up area, resulting in a steeper beach profile. Such a beach profile results in increased turbulence, a tendency for beach sand to be broken up into finer pieces and washed away, and a further narrowing of the beach. Eventually, the beach can disappear, and wave attack occurs directly on the engineered shore, increasing the possibility of structural failure. Bulkheads can also increase the intensity of longshore currents, again hastening removal of beach sand (Pilkey *et al.* 1980).

Komar (1983) showed that the mining of beach sand helped increase downdrift erosion of Siletz Spit, Oregon. Though not prevalent today as a commercial operation (Everts 1980), beach sand mining can also occur on lesser scales, as homeowners use beach sand to build up land behind bulkheads and other shoreline modifications. In addition, beach sand is sometimes bulldozed from the beach to the dune as a stopgap buffer against storm waves (Nelson 1991; Thieler and Young 1991; Wells and McNinch 1991). While such a practice can provide temporary backbarrier protection, it may also exacerbate beach and downdrift erosion, as the beach profile is steepened and sand is temporarily removed from littoral drift (Tye 1983).

Beach nourishment can be used to mitigate the effects of shoreline modification, though care must be taken not to use sediment that is too fine, consequently being washed off the beach (Dolan 1976; Pilkey *et al.* 1980). Conversely, coarser sediments may increase beach slope, lessening beach width so that dune scarping may occur during high water events. In addition, sand should not be taken from other barrier storages (e.g. dunes, offshore, backbarrier wetlands), thereby jeopardizing natural buffers to storm-related stresses. Artificial bypasses can be implemented to mitigate the impacts of sand traps such as jetties, reintroducing trapped sediment to the littoral drift. However, as the effects of both beach nourishment and artificial bypasses are only temporary, such measures generally must be conducted on a continuous basis, considerably adding to monetary costs (Pilkey *et al.* 1980). Nordstrom (1987) noted that beach nourishment programs may initially mask potentially severe erosion problems that become all too apparent once the program is interrupted.

At Long Point, shore protection is primarily found along Hastings Drive, near the lake end of the causeway and near Woodstock Avenue (Transition Zone), and the Inner Bay (Fig. 3). Broken concrete and armour stone revetments are common along Hastings Drive. In the Transition zone, approximately 400 m of gabions have been placed at the west, while approximately 550 m of steel sheet piling predominate in the eastern end (Philpott Associates 1989). The shoreline in the Inner Bay is primarily protected with vertical wall structures.

B. Dune and Barrier Flat Subsystems

Large dune complexes are likely to occur in areas with: active sediment supply; impeded alongshore transport; strong onshore winds; low precipitation and humidity, which decrease threshold velocities; low, wide beach angles; and, where appropriate, large tidal ranges, which expose a larger source area for aeolian transport (Davies 1980). Maintenance of the dune system requires an adequate sediment supply dependent on the volume of beach sediment supplied by nearshore and alongshore sources, and the existence of a wide, vegetation-free backshore (Davidson-Arnott and Pyskir 1988). Aeolian transport in the dune zone is restricted by vegetation. Thus, more significant transport is generally more important on open, vegetation-free surfaces (Armon 1979).

Several authors have noted the many environmental factors which affect the distribution of vegetation on coastal dunes, including differences in soil moisture, substrate stability, burial rates, and exposure to salt and desiccating winds (e.g. Godfrey and Godfrey

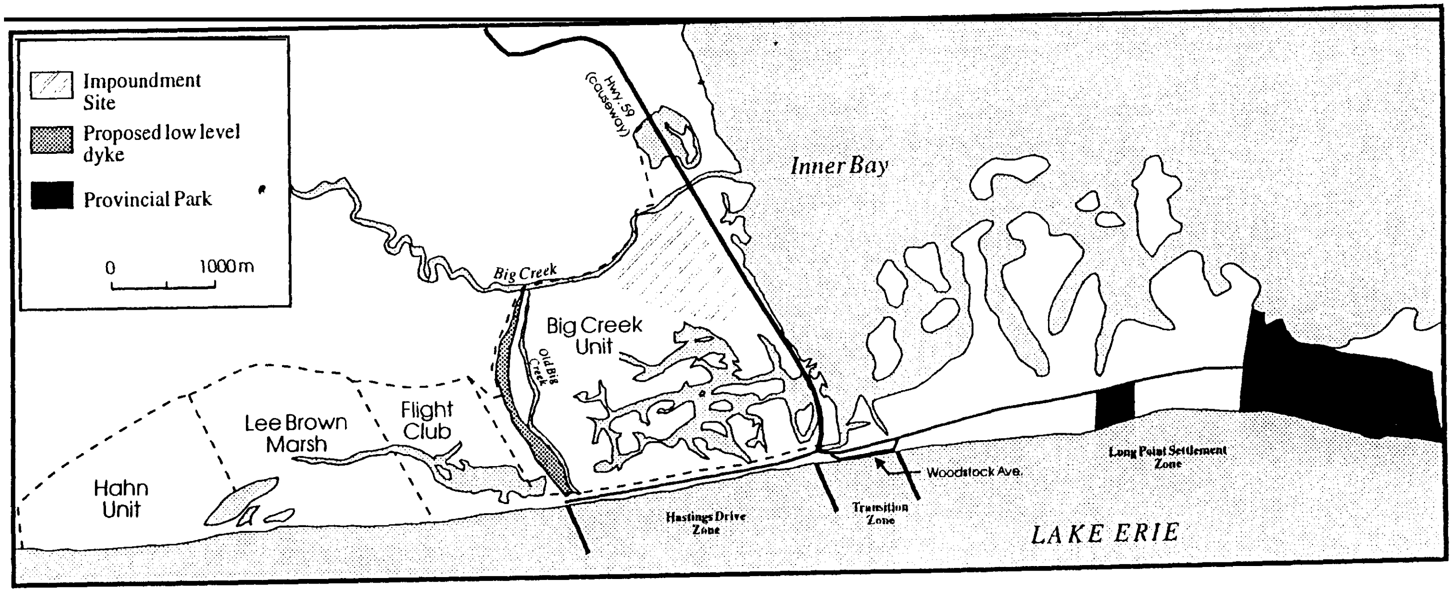

Fig. 3 Proximal Zone of Long Point

1976; Oosting and Billings 1942). Generally, early colonizers such as sea oats (*Uniola paniculata*) **are** the most adapted to high stress conditions, though even these hardy species show different distributions relative to tolerance to burial, flooding, heat stress and disturbance (Godfrey ***et al.*** 1979; Mendelssohn ***et al.*** 1983).

Different efficiencies in dunebuilding plants have also been noted by several authors (e.g. Godfrey ***et al.*** 1979; Mendelssohn ***et al.*** 1983). For example, sea oats generally produces high steep dunes up to 5 m high, while marsh-hay cordgrass (*Spartina patens*) generally produces low profile dunes (less than 1 m)(Mendelssohn ***et al.*** 1983). Vegetation can also affect dune shape. For example, beach tea ***(Croton punctatus)*** and dune elder ***(Iva imbricata)*** produce large, hummocky dunes, while American beach grass (*Ammophila breviligulata*) produces gently sloping dune ridges (Mendelssohn ***et al.*** 1983).

Distribution of dune plant species can significantly impact barrier morphology and stress-response (Godfrey 1977; Godfrey ***et al.*** 1979). For example, Godfrey ***et al.*** (1979) found that barrier systems in Massachusetts are dominated by densely growing American beach grass, and are characterized by high, continuous dunes which restrict overwash. American beach grass grows best where flooding and heat stress is minimized, and sand is continually added to the dune system. Dune development is also assisted in the north by a larger tidal range, which exposes a wider beach source for aeolian transport. Conversely, barriers in North Carolina are colonized primarily by the more heat resistant sea oats. While sea oats is more resistant to heat stress, the plants do not grow laterally as rapidly as American beach grass, nor as densely. As a result, dunes tend to be lower and discontinuous, allowing extensive overwash.

Rosen (1979) noted that wave-eroded dune crests limit landward aeolian transport and dune growth. Dune crests can impede landward transfers, resulting in alongshore aeolian transfers at the dune base which extend the foredune line in flat areas, helping repair dune breaches or build up newly formed barrier segments.

Armon (1980) found that both higher and seaward facing dunes have a higher risk of blowouts, as each are more exposed to high wind stress. In addition, seaward located dunes are commonly vegetation-free, often being partially eroded by storm waves. On the other hand, smaller dunes are more susceptible to destruction by extreme storm events, providing less protection to the backbarrier environment (Thieler and Young 1991).

Dolan (1972) suggested that erosion of a microtidal barrier’s dune face and loss of beach width may be accelerated by a high, continuous dune line, as storm wave energy directly attacks the dune line rather than being dissipated on overwashed beaches and dunefields. As a result, the dune line may become severely eroded and scarped. Similar to bulkhead effects, waves attacking the beach may also rebound off the high dune and carry sand offshore, gradually narrowing the beach. The difference between beach widths on natural and altered barriers can be quite dramatic. For instance, in North Carolina, Dolan (1973) found unaltered barriers to have beach widths ranging from 125 to 200 yards wide, while those barriers with artificial dune lines had beach widths of 30 yards or less. Castro (1988) has shown that artificially constructed and maintained dune lines restrict inland sand transport, and may remain scarped throughout the year.

Armon (1980) suggested that dune restoration might be better conducted by establishing dune patches rather than continuous dune lines. Dune patches have a better chance of survival during washover events, and facilitate rapid dune accretion as sand can move into the patches from all sides.

Leatherman (1979) found that dunes do not accelerate erosion on adjacent beaches during storm events. The author noted that dunes may serve as wave reflectors during storm events, but wave tank experiments suggest that such effects are probably minimal. Rather, dunes primarily mitigate storm impacts by acting as: 1) sediment storages; 2) energy dissipators; and 3) barriers to storm waves and over-wash. However, continuous dune lines may also act as a dam to bayside storm surges, increasing flood levels on the backbarrier (Godfrey and Godfrey 1976). Armon (1980) noted that high dunes in more sheltered environments may not provide a reservoir for beach sand during storm events. While eroded dune sand moves offshore, a lack of foreshore recovery may prevent its return.

Storm surges and waves keep permanent plant life off the beach and berm, while vegetation near the beach is adapted to flooding, burial, and harsh conditions (Cowles 1899; Olson 1958). Dolan *et al.* (1973) demonstrated that diversely vegetated, fertilized, high stabilized dune lines stop over-wash and salt spray, allowing plants that would be found much farther from the beach on natural islands to survive on the back slope. Such ‘out-of-place’ plants are not well adapted to flooding, burial, and/or salt spray, and are often killed by storm breaching of dunes.

At Long Point, the wide beaches associated with seasonally low water levels or periods of record low lake levels generally promote dune repair and growth of embryo dunes (Olson 1958) by protecting the foredune and colonizing plants from wave attack, and acting as a source area for sediment entrainment by wind (Saunders and Davidson-Arnott 1990). High winds are generally an eustress for aeolian activity when not accompanied by high wave activity in the nearshore zone (i.e. with offshore winds or low water levels). Generally, maximum sediment supply for dune growth occurs during the fall months when seasonal water levels are low, the winds are the strongest, and the beach is not frozen (Law and Davidson-Arnott 1991). Deposition during the typically low wind conditions from late spring to early fall generally takes place in the embryo dune vegetation, though entrainment is enhanced as gradually lower water levels expose a wider, drier beach (Law and Davidson-Arnott 1990). Sediment transported from the beach to the dune must be replaced by sediment supply updrift; otherwise the beach narrows, leading to eventual dune cliffing and return of sediment to the beach (Psuty 1988). Likewise, increases in dune storage through dune building projects can temporarily decreasing net drift, increasing the potential for downdrift erosion. A continuous interaction exists between beach and dune, controlled primarily by beach and dune sediment budgets (Davidson-Arnott 1988)

Dune vegetation cover is generally sufficiently dense from late April to late November to limit high wind distress, preventing much interdune aeolian transport (Law and Davidson-Arnott 1991). Winter dieback, breakage, and burial of pioneer vegetation increases vulnerability to erosion by seasonally high winds (offshore and onshore), though entrainment might be limited by frozen or snow-covered conditions (Davidson-Arnott and Law 1990). Aeolian activity is thereby increased in exposed areas of the foredune zone, leading to some windward deflation, and augmenting the importance of shrubs and trees as zones of stabilizing vegetation on the dune crest and lee slope (Law and Davidson-Arnott 1991).

Recovery of severely cliffed dunes is generally slower than areas which have been overwashed (Saunders and Davidson-Arnott 1991; Olson 1958) Recovery of over-wash areas is aided by the presence of plant propagules, proximity to water table, and organic material. On the other hand, recovery of more vertical dune scarps is hampered by geomorphic instability due to slumping and greater blowout vulnerability, as well as higher moisture stress due to larger distance from the water table and greater exposure to desiccating winds.

Dune vegetation at Long Point ranges from the sparse, newly vegetated dunes to the older, complex wooded dune ridges (Planck 1982). Soil layers are extremely thin and susceptible to disturbance even in the older ridges. Accordingly, vegetation removal normally results in immediate wind erosion and greater potential for blowouts and dune migration.

Alteration of vegetative processes is a type of human stress extremely prevalent in the dune and barrier flat system. Leatherman (1979) discussed the trampling effects of pedestrian and vehicular traffic in destabilizing dunes by disturbing vegetation. Distresses include blowout initiation, slowing dune recovery, as well as lowering dune crests, thereby making barriers more susceptible to overwash events. Human stresses which disturb the vegetative cover of dune systems may result in blowouts that may not be repaired for years. The effect of intensive logging in destabilizing vegetation cover to allow increased wind erosion has been observed on many barrier systems, including Curritack Spit, North Carolina (Hosier and Cleary 1987). Barrier stress by grazing has also been noted by several authors (e.g. Godfrey and Godfrey 1973; Oosting and Billings 1942). Destabilized dunes can migrate into previously stable areas, covering vegetation, ponds, and wetlands (Leatherman 1979).

Dune system stress has resulted from the intense use of Long Point, precipitated by the building of a causeway across Walsingham swamp in 1927-28, thereby connecting Long Point with the Port Rowan mainland (Barrett 1977). Human activity is currently concentrated in the proximal end of Long Point, primarily in the form of cottaging and the Long Point Provincial Park. Between 1945 and 1972, the number of cottages increased from about 50 to almost 900, including approximately 50 permanent homes (Heffernan and Nelson 1979). During 1985-86, the number of residences were considerably reduced by heavy winter storms during the high water levels of 1985-86. In one storm alone, over 70 cottages were lost in the Hastings Drive area. Nonetheless, in 1988 the Long Point community still consisted of 760 seasonal dwellings and 104 permanent homes (Warner 1988). In Long Point Village, of 199 buildings along the southern lakeshore, 186 are 1 story residences (Philpott Associates 1989). Most cottages on the Hastings Drive and near the causeway are located near the average water line, while cottages closer to the provincial park are located on top of a 1 - 2.5 m high dune system (Philpott Associates 1989).

Buildings can have pronounced effects on aeolian transfers, trapping windblown sediment and substantially reducing transport rates by both offshore and onshore winds (Nordstrom and McCluskey 1985). Often, trapped sediment is removed by earthmoving equipment, and lost to the barrier system (Nordstrom 1987). Wind scour of dunes may also be increased at the base of buildings. Residential development can also be accompanied by other activities that impact aeolian transfers, including bulldozing or removing protective dunes, or replacing natural vegetation with lawns, thereby limiting source areas and the propagation of dune-building plant species. Bulkheads can prevent the exchange of sand between beach and dunes, either through overwash or aeolian transfers (Pilkey *et al.* 1980).

Traffic (mechanical and pedestrian) and park facilities such as camping sites and parking lots can both destabilize dune systems (Ralph and Heffernan 1978), as well as reduce the availability of pioneering species important for dune repair (Saunders and Davidson-Arnott 1991). Ralph and Heffernan (1978) noted that park management practices such as clearing tree understories, plowing sand from parking lots, and using all-terrain maintenance vehicles have added to dune stress. Dune recovery can be hindered if pioneering plant propagules (e.g. seeds, rhizomes) are not found updrift and close to the site. For example, Saunders and Davidson-Arnott (1991) found that updrift cottage and park development had decreased the typical habitat (embryo dunes), and therefore extent of typical plant pioneers (e.g. American beach grass and switch grass *Panicum virgatum).* Other dune species (e.g. wild grape), though more resistant to trampling stress, are not adapted to initiating the growth of embryo dunes important to dune repair. The shortage of dune pioneers, augmented by heavy losses following storm stress, slows the rate of downdrift dune repair as much of the sediment supplied by aeolian transport from the beach is not trapped by embryo dunes, but is rather deposited on the crest and lee slopes of the dune system.

Snowfencing has been used since 1974 to rebuild dunes at the Long Point Provincial Park (Cooper 1980), with only site-specific benefits. Sand buildups were localized, while areas between snowfences was still being eroded (Heffernan and Ralph 1978). Dune regeneration through planting vegetation has also been conducted on park lands, beginning in 1977 (Cooper 1980).

Destabilization can also occur in Long Point's older dune flats due to lumbering, grazing, and other activities contributing to vegetation removal. Commercial logging on Long Point began around 1860 as mainland forests began to be depleted (Barrett 1977). Wind erosion and blowouts soon became widespread, especially on Long Point's dune ridges. The Canadian government, unable to prevent unlawful cutting of timber, sold most of Long Point to the Long Point Company in 1866 as a hunting reserve. Lumbering virtually ceased in 1873, as stocks were all but depleted. It was also realized that removal of trees increased wind erosion (Laidler 1944), and the Long Point Company restricted further logging (Barrett 1977). Occasional logging was allowed by the Long Point Company at the turn of the century, primarily from burnt-over land. During the Depression, and into the 1940's, selective lumbering of mostly white pine, white cedar, and red oak was reintroduced, though on a limited scale and combined with extensive reforestation (Barrett 1977; Heffernan and Nelson 1979). Some evidence of logging roads on dune ridges still exists (Heffernan 1978).

Grazing pressures occurred on Long Point as early as the late 1700s, and continued well into early part of the twentieth century (Barrett 1977). Grazing and browsing by deer, restocked at Long Point as early as 1875 (Barrett 1977), may also contribute to devegetation (Heffernan 1978; Heffernan and Nelson 1979).

Fire also has played a role in destabilizing Long Point's older dunes. The earliest recorded fire occurred in 1881, and resulted in extensive damage of the Long Point Company marsh and dune ridge vegetation (Barrett 1977). Subsequently, six significant fires have occurred from 1933 to 1978 (Heffernan 1978). Since 1965 there have also been several small fires started by careless picnickers. Fire damage can remove vegetation, as well as induce damaging heartrot. Vegetation in burned areas is also slow to recover, as nutrient supplies are lost and underlying sands are exposed to wind stress, creating extensive blowouts before plant cover is re-established (Planck 1982). Accidental fires remain a possibility due to human activities such as camping and picnicking in the Long Point Provincial Park (McKeating 1980), as well as use of the proposed walking trail in the Long Point National Wildlife Area.

Washovers

Over-wash is defined as the transport of water and sediment from the beach through the dune system, sometimes to the backbarrier (Leatherman 1979). As an overwash event cuts through a dune line, additional sediment is eroded from the throat, transported inland, and deposited leeward of the dunes (i.e. washover fan). During very intense storms, large sections of barrier dunes may be flattened, forming washover flats. Regardless of size and magnitude, washovers are generally caused by the synergistic interactions of onshore wind, storm surge, and high energy waves (Fisher and Stauble 1978), though they can occur during extreme high water events (e.g. high spring tide) in low lying areas (Leatherman 1979). The extent of washover damage is dependent on storm intensity, frequency of storm events relative to recovery rates, and dune size and stability (Fisher and Stauble 1978). Low-profile areas, often due to blowouts, traffic, or previous washover events, are generally more susceptible to overwash (Leatherman and Zaremba 1987). Several authors have found that continuous dune vegetation restricts overwash, limiting landward sand transport (e.g. Dolan 1972; Armon 1979; Leatherman 1979).

A number of studies have concluded that overwash is integral to barrier stability. In fact, restricting over-wash can have negative impacts on other barrier subsystems. For example, Godfrey and Godfrey (1973) found that artificial dune-dike systems can cause drastic erosion in backbarrier environments by preventing overwash fans from rejuvenating backbarrier wetlands with nutrients, thereby jeopardizing their value as erosion buffers. Several authors (e.g. Dolan *et al.* 1973; Godfrey and Godfrey 1976) have suggested that overwash events provide landward sediment transfers necessary for barrier transgression. Washovers may temporarily destroy dune ridges, but in turn cause a widening of the barrier system (Hosier and Clear-y 1977). Over-wash deposits also serve as source areas for the aeolian transfers necessary for storm recovery (Fisher and Stauble 1978) and landward transfers, while barrier dune breaches also act as corridors for landward aeolian transport (Armon 1979). Similarly, Godfrey and Godfrey (1973) demonstrated the importance of washover fans as sediment sources for the maintenance and growth of dune areas, while Godfrey and Godfrey (1976) emphasized the role of overwash in helping fill old inlet channels. Several authors (e.g. Fisher and Stauble 1978; Leatherman and Zaremba 1987) have stressed the importance of washover fans as temporary stores of sand which are returned to the beach by offshore winds.

Hosier and Cleary (1977) stressed the cyclic pattern of storm-induced over-wash, characterized by a gradual narrowing of the foredune ridge, followed by eventual breaching and overwash. During average conditions, the foredune ridge is repaired, further developing until the next stress event. The authors noted that rapid development of dune ridges may restrict frequent over-wash events, as those occurring on the Outer Banks, North Carolina (e.g. Godfrey and Godfrey 1973).

Dune recovery of washovers can be extremely variable, dependent on shoreline orientation and wind exposure (Armon 1980), washover size and depth, sediment size (Godfrey and Godfrey 1976; Cleat-y and Hosier 1979), and human activity (Leatherman and Zaremba 1987). Shoreline exposure and orientation may increase frequency of overwash events. Smaller washovers are generally repaired more rapidly than washover flats, which are generally subject to repeated overwash until dunes redevelop from drift lines (Leatherman 1979; Leatherman and Zaremba 1987). Low-lying washover flats can remain barren for long periods of time, constantly being reactivated by further over-wash events and/or wind erosion (Leatherman and Zaremba 1987). More exposed, lower surfaces are more prone to subsequent over-wash. Lower washover surfaces, either due to hydraulic activity or wind deflation, are generally moister (i.e. close to water table), inhibiting sand entrainment (Armon 1980). Dunes prevent overwash from becoming too frequent or severe so that vegetation recovery takes place between storm-related stress events (Godfrey and Godfrey 1973). Clear-y and Hosier (1979) suggested that washover recovery may also be dependent on sediment size, where finer-grained environments may be repaired more quickly through aeolian transfers, decreasing overwash recurrence. Washover recovery can also be slowed by human impacts such as trampling and off-road vehicles, or reductions in sediment supply (Leatherman and Zaremba 1987).

Parking lots and streets oriented perpendicular to the beach may significantly increase overwash penetration, channelling storm surges inland (Hall and Halsey 1991). Conversely, buildings such as condominiums and hotels may restrict overwash flows. Similarly, the formation of ebb scour channels, produced by the ebb flow of storm surges, is enhanced by the presence of perpendicular street ends, public accesses, partially failed shoreline protection, open drainage areas or water bodies, as well as the absence of vegetative cover (Lennon 1991). Ebb channel formation is inhibited by continuous dune ridges and intact seawalls.

Washover events at Long Point are generally perceived as being distresses to stabilizing vegetation and bayside aquatic communities (e.g. Bayly 1979). However, washovers and inlets help maintain the integrity of a sandy barrier by moving sediment landward, especially in areas with a negative sediment budget (Project Management Team 1989). Washovers and inlets generally occur due to major storm events during high lake levels, though such erosion is generally restricted in the winter, as the shoreline is often protected by an ice foot and lake ice cover from December to April (Law and Davidson-Arnott 1991).

Fisher (1989) investigated the relationship between overwash frequency, sediment budget, and lake level fluctuations at Long Point. He found that a reduction in mean lake level leads to a temporary reduction in overwash occurrence, and that overwash occurrence depends ultimately on storm wave climates and the local sediment budget.

6. MANAGEMENT IMPLICATIONS

Long Point's stress-response and recovery is greatly impacted by fluctuating water levels, stress intensity and frequency, as well as environmental gradients such as differences in sediment storage and supply. Aspects of these stress-response variables may be articulated in terms of three main conceptual challenges to management: dynamic stability, spatial integrity, and temporal heterogeneity. These in turn form the framework for management principles that might be used to evaluate and guide management of the geomorphic environment of the Long Point barrier system.

A. Dynamic Stability

Fluctuating Great Lakes' water levels and dynamic shore processes help create a naturally well-regulated sandy barrier resource system. Sandy barriers are classic examples of dynamic stability, capable of adjusting to storms and fluctuating water levels. Long Point is in constant flux, characterized by continual changes in beach and dune profiles, as well as formation of inlets and washovers during storm events. Implicit to the concept of dynamic stability are the notions that barriers are dependent on and adapted to stress (stress-dependency), and that the effects of a perturbation produce different subsystem responses, often dependent on environmental conditions (stress-response hierarchies).

Stress-Dependency

Riggs (1976) emphasized the storm-dependency of barrier systems, noting that storm energy drives many barrier processes such as overwash and inlet dynamics, and that barriers have the ability to adjust to constantly changing energy regimes, thereby maintaining a dynamic equilibrium. Similar to other stress-dependent systems, Great Lakes' sandy barriers are adapted to and dependent on periodic stresses (i.e. pulsed inputs) as driving forces and system catalysts. Natural stress-response is typified by a cyclic maintenance characterized by sediment inputs stimulated by stress which are eventually stored in various sub-systems to help protect the barrier during the next stress cycle. While higher intensities of natural stress may cause widespread degradation in the short-term, destructive effects are rapidly countered by stimulating effects of the perturbation (e.g. increases in sediment supply) and transfers of sediment from one subsystem to another. Natural stresses particularly important to barrier maintenance and development include high and low water events, high wave energy, storm surge, and high winds.

Principle 1: Management requires recognition and minimal restriction of the natural stresses which drive geomorphic processes essential to barrier maintenance and development.

Stress-Response Hierarchies

Categorizing barrier stress-response is complicated by the hierarchical nature of subsystems, as stress effects may vary significantly at different system levels. For example, high winds may contribute to beach erosion, but help build and repair dune systems that both protect the backbarrier during average conditions, as well as act as sediment storages during periods of stress (e.g. storm events).

Principle 2: Management requires restricting the repression of site-specific distress at the expense of system eustress.

Proper recognition of dynamic stability must also include consideration of two other interrelated concepts: spatial integrity and temporal heterogeneity.

B. Spatial Integrity

Stress Buffers

Sandy barriers are maintained by a complex linkages of aeolian and hydraulic sediment transfers. The availability of sediment, whether from offshore, updrift bluffs, river sources, or the barrier itself, is key to barrier stability and evolution (Kraft *et al.* 1979). Ignoring the importance of hydraulic and aeolian linkages by decreasing sediment supply (e.g. armouring, beach mining), stores (e.g. dredging, dune destabilization), or transfers (e.g. groins, artificial dunes) can increase stress susceptibility as well as slow recovery processes. Linkages especially important in the barrier environment include longshore transport, aeolian transport, washovers, and inlet transfers. The additional role of sand storages in dunes, beaches, and nearshore bars as stress-buffers has been emphasized elsewhere (e.g. Riggs, 1976).

Principle 3: Management requires protection of sediment sources essential to continued growth and maintenance of a sandy barrier (e.g. bluff and offshore sources).

Principle 4: Management requires restriction of impediments to sediment transfers essential to barrier development and the mitigation of natural stress, including longshore drift and landward transfers through aeolian and hydraulic processes.

Principle 5: Management requires protection of sediment storages essential to natural stress mitigation and barrier protection (i.e. dunes, beaches, and nearshore bars).

Environmental Heterogeneity of Stress-Response

The model also illustrates the importance of environmental heterogeneity for dynamic stability and stress-response. Barrier subsystems are clearly susceptible to different stresses, while similar systems can have very different vulnerabilities, dependent on environmental conditions. Several authors have noted the importance of environmental heterogeneity in other barrier systems. For example, Godfrey (1977) recognized that the relative significance of barrier processes such as dune building and migration, littoral transport, inlet formation, and over-wash depend on environmental conditions, including prevailing winds, wave regimes, water levels, storm frequencies, shoreline orientation and configuration, offshore profiles, and natural vegetation. Similarly, several authors have noted regional variations in washover events (Butler *et al.* 1980; Leatherman 1981; Pilkey *et al.* 1980) as well as dune building (Leatherman *et al.* 1978). Environmental heterogeneity also plays a role on individual barriers. For example, Hosier and Cleary (1977) noted over-wash events can dramatically vary both temporally and spatially due to differences in dune integrity and storm climates, resulting in heterogenous physiographic units in various stages of stress-recovery.

Several authors have shown that the proximal and central zones of Long Point are controlled by a negative sediment budget, leading to a transgressive shoreline where over-washing (Fisher and Davidson-Arnott 1992), dune cliffing and blowouts (Saunders and Davidson-Arnott 1991), and inlet formation (Davidson-Arnott 1988) are more common. For example, Fisher (1989) found that 50-65 % of the proximal and central regions were subject to overwash during the record high water levels of 1985-86, while much of the remaining foredune was cliffed. In comparison, the wider beaches, abundant vegetation, and greater number of embryo dunes in the distal end resulted in only 2% of the shoreline being subjected to similar destruction. The lack of sediment storage increases stress susceptibility, so that even moderate stress levels can be considered as a system distress, leading to a greater propensity for washovers, inlet formation, and blowouts. Saunders and Davidson-Arnott (1991) found that variable rates of dune recovery are due to variations in sediment supply, vegetative cover and types, synergistic stress, and preexisting conditions (i.e. stress regimes).

Presently, only 8-10 km at the distal end of Long Point have a positive sediment budget, characterized by a wide, prograding beach, longshore sandwaves, and the formation of new dune ridges (Davidson-Arnott 1988). The positive sediment budget of the distal zone promotes greater development of longshore sandwaves, wider beaches, and a more extensive and vegetated embryo dune zone (Saunders and Davidson-Arnott 1991). A greater number of longshore sandwaves and wider beaches help dissipate wave energy, lessening storm stresses and protecting the embryo dunes (Stewart and Davidson-Arnott 1988). In addition, these features act as source areas for aeolian transport. Finally, the extensive, vegetated embryo dune zone is less susceptible to wind erosion, trapping aeolian sediment and acting as an additional buffer to intense high wave action, thereby helping to protect the dune system. Being vegetated and wider, there is less chance of complete destruction by high wave stress, while a greater supply of pioneer propagules allow for greater recovery rates.

Princinle 6: Management requires recognition of the spatial variability in stress-response by restricting additional stress of high stress areas with slow recovery periods.

C. Temporal Heterogeneity

Temporal Scales of Stress-Response

Long Point's natural stress-response must be considered at three temporal scales: seasonal, long-term cycles, and evolutionary. While the former two primarily refer to seasonal and long-term differences in lake levels, the latter reflects consideration of changing environmental conditions.

The cyclicity of seasonal and long-term lake levels clearly has a marked effect on barrier stress-response. Cyclic pulsed inputs generally help ensure the long-term stability, diversity, and development of Long Point. A combination of high water levels and intense storms can cause severe foredune cliffing, over-wash, and initiation of blowouts (Saunders and Davidson-Arnott 1991). The reduced beach widths associated with high water levels can increase the erosion susceptibility of dune systems, even during moderate storms. Alternatively, falling lake levels provide a wider, often drier beach which both provides a source of aeolian sediment for embryo dune repair and foredune development, as well as serves to protect the backshore from moderate stress levels that may have been damaging at higher water levels.

The timing of a stress relative to such natural cycles helps determine barrier response. For example, high winds are generally less an eustress for aeolian activity during high lake levels, while lower lake levels lessen the distress characteristic of high energy storms. Obviously, the simultaneous occurrence of two or more stresses may render each more or less significant than if each stress was acting alone (i.e. synergism-antagonism). Human stresses tend to occur irrespective of natural stress cycles. However, activities such as dune destabilization and dredging during generally low stress periods (e.g. low water levels) may accentuate stress effects during periods of intense stress (e.g. high water levels and storm events).

Principle 7: Management must recognize the cyclicity of natural stresses, preventing activities that might heighten stress-susceptibility during natural stress events.

While beach profile adjustments lag behind fluctuating water levels (Hands 1983), stabilization eventually occurs at low lake levels. Thus, low lake-level beaches are then controlled by the prevailing sediment budget and wave climate regime. Both are conditional on barrier evolution. Major factors contributing to barrier evolution include nearshore and offshore morphology, source and size of sediment, natural stress-regime, and water level fluctuations (Kraft *et al.* 1979).

Sediment budgets can vary temporally on individual sandy barriers. At different points in time, sandy barriers can have positive, negative, or stable sediment budgets. For example, Long Point has evolved over several thousand years as a result of variations in longshore sediment transport, deposition at the distal end of the spit, and changing wave climates. Coakley (1983) suggested several interrelated factors controlling Long Point's evolution. Variations in rates of bluff recession and the potential rate of longshore transport impact sediment supply. Deposition at the distal end occurs as sediment transport slows due to refraction of waves around the end of the spit, the deeper water at the distal end, and a greater exposure to north-easteriy waves. As the spit grows into the deeper water at the distal end, the rate of growth slows as the volume of sediment needed to reach the surface increases. Continued growth at the distal end of the spit results in the proximal end becoming more sheltered from easterly and north-easterly winds, increasing the net easterly sediment transport and causing a negative sediment budget. Erosion and northward retreat of the proximal end is further enhanced by the continual erosion and northward recession of the bluffs to which Long Point is attached.

Principle 8: Management must accept and plan for inevitable, long-term evolutionary changes.

Stress Frequency and Recovery

While stress-dependent systems such as Long Point may have relatively rapid recovery rates, system stability and recovery is dependent on a normal range of frequencies and intensities. While the range may be altered gradually through barrier evolution, system distress can be enhanced in the short-term if the frequency of stress is higher than a systems ability to recover (i.e. relaxation time). For example, considerable damage can occur if a storm greatly reducing the width of the beach and embryo dune zone is followed by another storm before recovery processes can take effect. Similarly, overwash sites may be more susceptible to repeated high wave stress during high water levels, as they are generally lower in elevation, slowing recovery rates of both dunes and wetlands. In addition, the importance of lake level fluctuations, while increasing the damage potential of even moderate storms, does not negate the probability of severe storm damage during average or even below average lake levels.

Many human stresses tend to be chronic rather than cyclical (i.e. ramped inputs), not allowing for natural recovery processes to increase the subsystem sediment storages that are crucial for stress resistance and mitigation. In addition, the cumulative and synergistic nature of most human stresses increase stress intensities and frequencies even further, often resulting in system distress. For example, bulkheads often increase wave scour and beach sediment loss, inhibit aeolian transfers, and tend to coincide with other human stresses (e.g. residential development, vegetation removal). Due to the buffering capabilities of barrier subsystems, there may exist a time lag between the onset of stress and observable impacts. Stresses with no noticeable impacts over the short-term may actually produce chronic long-term impacts. For example, shore protection may only show negligible distresses in the short-term, though may contribute to a gradual deterioration of dune and downdrift systems that becomes all too apparent in times of additional stress (e.g. high lake levels).

Ironically, human stresses are more prevalent in the proximal and central ends, increasing stress levels even further. Many human stresses either disregard barrier processes (i.e. dune destabilization) or involve inappropriate repression of site-specific distress at expense of eustress for system (e.g. shore protection and dune building restricting downdrift sediment transfer). In either case, cumulative and synergistic effects increase stress intensities and frequencies even further, often resulting in system distress.

Principle 9: Management requires controlling or mitigating the frequency of human stresses to limit system distress and accommodate natural recovery processes.

The evaluative principles developed through the ecological-human stress model will be used in the next section to assess how management policies and practices of a selected agency at Long Point recognize issues of dynamic stability, spatial integrity, and temporal change.

7. EVALUATION OF LONG POINT SANDY BARRIER MANAGEMENT

While a number of federal, provincial, and local agencies are involved in managing the Long Point sandy barrier, this report aims to illustrate how the evaluative principles developed in the preceding section can be used to assess environmental management policies and practices. To this end, those principles (Table 2) are applied in this section to the policies and practices of one agency, the Long Point Provincial Park.

A. Long Point Provincial Park Policies and Practices

Most of Long Point west of the Old Cut and east of Big Creek Marsh was retained by the Crown following the sale of the rest of the Point to the Long Point Company in 1866. This land was surveyed in 1920 by the Crown Lands Department to be sold to the public. As a result of public interest, however, a portion of this land (800 ha) was established as Long Point Provincial Park in 1921 under the authority of the Long Point Park Act. By 1944, several parcels were added, enlarging park lands to 930 ha. However, development pressures were already evident in 1923, when a subdivision plan was drawn up for the park showing 69 cottage lots, 3 park lots, and 1 lot designated for an amusement park. During the next 34 years, most parkland was sold for cottage development. Roads and cottages were being built as early as 1938, and by 1940 there were 100 cottages and 1 permanent residence in the park. In 1944, cottage leases were issued for 21 year intervals. In 1955, the park became designated under the Provincial Parks Act, and contained approximately 450 cottages and 6 permanent residences. Wanting to increase its tax base, the Township of South Walsingham then applied to the provincial government to have the cottages placed under its jurisdiction rather than the Department of Lands and Forests. The Department began selling previously leased lots to the cottagers in 1959, decreasing the size of the original park to 5 ha. In 1961, 325 ha east of the original park were expropriated and added to the provincial park. Since 1960, the Provincial Park has increased its number of campsites from 100 to 265, though presently a moratorium exists on further expansion.

The park presently includes 261 campsites, parking for 800 cars, a 6.5 ha picnic area,

Table 2

Evaluative Principles for Sandy Barrier Management

Principle 1: Management requires recognition and minimal restriction of the natural stresses which drive geomorphic processes essential to barrier maintenance and development (natural stress protection).

Principle **2:** Management requires restricting the repression of site-specific distress at the expense of system eustress **(system eustress protection).**

Principle 3: Management requires protection of sediment sources essential to continued growth and maintenance of a sandy barrier (e.g. bluff and offshore sources)(sediment **source protection).**

Principle 4: Management requires restriction of impediments to sediment transfers essential to barrier development and the mitigation of natural stress, including longshore drift and landward transfers through aeolian and hydraulic processes (sediment transfer protection).

Principle 5: Management requires protection of sediment storages essential to natural stress mitigation and barrier protection (i.e. dunes, beaches, and nearshore bars)(sediment storage protection).

Principle 6: Management requires recognition of the spatial variability in stress-response by restricting additional stress to high stress areas with slow recovery periods (spatial variability).

Principle 7: Management must recognize the cyclicity of natural stresses, preventing activities that, might heighten stress-susceptibility during natural stress events **(stress cyclicity).**

Principle **8:** Management must accept and plan for inevitable, long-term evolutionary changes **(evolutionary change).**

Principle **9:** Management requires controlling or mitigating the frequency of human stresses to limit system distress and accommodate natural recovery processes **(human stress control).**

and 2.2 km of recreational beach. A parking area and access channel to a boat launch on the bay side is continually maintained and upgraded. Over 95,000 visitors came to the park in 1992, down from 128,000 five years earlier, and reflecting a Province-wide decline in Park use (Ministry of Natural Resources [MNR] 1992). Camping use of the park, however, has remained relatively constant at about 62,000 camper-nights annually. The average length of stay in 1992 was 3 .O days, the provincial average. In addition, up to 3000 people have used the beach in a single afternoon (Cooper 1980).

Combinations of natural stress events and public use have resulted in environmental deterioration and the need for dune rehabilitation. Snowfencing was first used in 1974 to rebuild foredunes eroded during the storms of 1972-73 (Ralph and Heffernan 1978). Further snow fencing was erected in 1977. However, sand buildups were localized, while areas between snowfences were still being eroded (Ralph and Heffernan 1978). Dune regeneration through planting vegetation has also been conducted on park lands, beginning in 1977 (Cooper 1980). Trampling pressures have also been addressed somewhat by moving campsites from the foredune area in 1974, and building a dune boardwalk in 1979.

In the absence of a master plan, interim management guidelines were prepared for the park in 1977 (MNR 1977). These guidelines provided both review of immediate problems as well as short-term solutions which would not alter overall park structure. (Cooper 1980). The management guidelines recognized that special park management techniques were required to respect the natural processes which were essential to well-being of both the park and the rest of Long Point. For example, the guidelines suggested that the day use zone in the new park be replaced with a camping area, though no campsites were to be built within 50 feet of the primary dune. In the absence of either earth or life science assessments done for other provincial parks, a visual inspection of park conditions indicated large areas of alteration and distress of the geomorphic environment, especially in the dune subsystem. As a result, the interim guidelines recommended an inventory of earth science features as well as research on dune crossing and rehabilitation techniques.

An environmental management study was initiated in 1978 (Ralph and Heffernan 1978) which acknowledged several elements of the dynamic stability, spatial integrity, and temporal heterogeneity of barrier stress-response. The authors noted the dynamic nature of the site relative to periods of high water, especially in terms of inlet formation. The importance of fluctuating water levels for dune recovery and repair was also stressed. The study also recognized the importance of littoral drift in maintaining Long Point, warning that sandtraps may distress the system.

The environmental management study primarily focused on the recreational stresses of the park's foredune, recognizing the trampling pressures of camping and picnicking on dune vegetation. Other pressures included plowing sand from park roads transferred inland by wind action. The plowing was found to make the lee side of foredunes steeper and more easily eroded. Park maintenance, including clearing of the understory of treed areas, as well as garbage removal, were identified as additional stresses. The clearing of treed areas by removing dead or dying trees, as well as pruning the lower branches of tress and shrubs, was found to increase wind erosion and possibly interfere with dune plant regeneration. Use of an all-terrain vehicle for collecting garbage and placing picnic tables on the dunes also added to trampling pressures.

Recommendations by Ralph and Heffernan (1978) recognized the importance of lessening recreational impacts and repairing the past damage so that the effects of natural stresses are not accelerated. Ralph and Heffernan (1978) suggested that the new park could use as many as 12 boardwalks to lessen trampling pressures. However, only one was built in 1979 (Cooper 1980), though more are planned. Fencing has also been suggested to direct beach access and control haphazard dune trampling and blowout initiation. Other suggestions in the report included limiting mowing, clearly identifying access routes to comfort stations and water taps, and moving picnic tables from the foredune to beach and backdune areas. Group camping was also to be restricted to designated campsites away from areas showing signs of inlet/blowout formation.

A long-term Management Plan was developed for the park in 1982 (MNR 1989). A primary goal is to "provide a variety of recreational opportunities which utilize the natural features and historic resources of Long Point Provincial Park while protecting the significant ecological features of the park". Park zoning and site-specific plans have recognized the importance of protecting special and unique features of the park. Features of particular relevance to this project include both the sand dunes and a dry prairie complex within park boundaries. Stresses of particular relevance to these natural features include the trampling pressures inherent in the recreational activities the park provides (e.g. camping, beach use, and hiking), as well as the risk of other types of vegetation removal (e.g. fires).

The Management Plan has recommended that the park be divided into three zones to accommodate development types and protect significant natural features. Two of these zones have particular relevance to recognizing and managing geomorphic stress. The development zone (33 ha) includes existing campgrounds, day use areas, and park buildings. Development in this zone is to be compatible with the natural environment, minimizing environmental impacts and recognizing the fragile nature of sandy soil found in the area. The natural environmental zone (96 ha) includes both the area of beach and dunes adjacent to the lake, as well as inland communities like the dry prairie meadows. Fences and dune crossings are the only development allowed in this zone, minimizing beach use impacts. Only low intensity uses such as nature viewing or research are allowed in the dry prairie, recognizing the fragile nature of plants which reduce soil erosion. Management in this zone will focus on protecting both landforms and natural communities, including both revegetating dunes and installing boardwalks.

Little additional development is planned for the park, intending only to increase operational efficiency and improve recreational opportunities, while still minimizing environmental distress. For example, the Management Plan has noted that the number of campsites within the park will not be increased, additional demand being directed to other nearby parks. Existing campsites are to be maintained and upgraded to prevent environmental distress from intense use. However, many campsites and picnic tables are still present on the dune system. In addition, park roads are still cleared of sand, which is then transported off park lands to be used as backbarrier fill for development, or dumped back into the updrift littoral system. Operation of vehicles off the roads within the Provincial Park is prohibited by the Provincial Parks Act, thereby restricting beach access by unauthorized vehicles.

The Management Plan recognizes the dynamic stability of Long Point in relation to fluctuating lake levels. No efforts are to be made to control natural processes like shore erosion through engineered structures. New developments are to be situated where they will not be threatened by erosion during the expected service life. For example, the Old Park's comfort stations have been threatened by erosion during high lake levels. The park will remove these buildings once deemed unsafe, only to be replaced following extensive evaluation. Possible alternatives may include restricting use of the threatened area to day-use only, serviced by smaller privies. The park also encourages on-site research, including management of dunes (Saunders 1990), overwash processes (Fisher 1989), and the role of sandwaves (Stewart 1986).

Implementing the findings of earlier studies, the Management Plan also recognizes the importance of beach grass and native vegetation in stabilizing dunes. Dune management has included the planting and protection of beach grasses, as well as the use of dune crossing boardwalks. While only a limited number of dune crossings have been constructed, further installation is still planned as demand requires and funding permits. The necessity of using native vegetation adapted to barrier stresses has also been recognized. Earlier attempts at dune stabilization such as conifer plantations of Red, White, and Scotch Pine have been deemed inappropriate as they have not thrived in the stressful environment, and have has an adverse impact on adjacent plant communities such as the dry prairie complex. These non-native plantations are to be gradually removed from the natural environment zone to allow more natural, stable plant communities to be established. However, a Vegetation Management Plan is still to be developed.

B. Evaluation

Early park policies and practices failed to recognize any of the evaluative principles pertinent to sandy barrier management. In particular, the leasing and later sale of cottage lots fostered many of the human distresses evident at the proximal end of Long Point today. However, both the subsequent interim guidelines and Management Plan have attempted to recognize the importance of **natural stress protection** by preserving essential barrier processes, as well as restricting the repression of site-specific distress to aid in **system eustress protection.** As no significant sources fall within park jurisdiction, no mention is made of **sediment source protection.**

The policies and practices have avoided use of shore protection structures to protect park facilities, recognizing the possible detrimental effects on the barrier system, as well as the importance of maintaining longshore drift to the remainder of the barrier (i.e. **sediment transfer protection).** However, management practices such as clearing sand from roads have compromised landward aeolian transfers that are equally essential for maintaining barrier integrity, especially in a negative sediment budget environment. In fact, background documents such as the environmental study imply that blowing sand is considered somewhat a nuisance as it covers up camping facilities and park roads. The net effect of dune rehabilitation and stabilization on such transfers has also not been considered in management policies.

On the whole, the park has made a special effort in **sediment storage protection** in regards to dunes and beaches through dune rehabilitation projects emphasizing use of natural vegetation, dune boardwalks, and restricting the use of shore protection. The environmental distresses inherent in past practices such as clearing campsites of vegetation, excessive mowing, and improper garbage removal have also been recognized. However, many campsites and picnic tables are still situated on the foredune.

Intense usage of recreational facilities at the park has created high stress levels in an area of Long Point that is least suitable for stress mitigation, mainly due to the negative sediment budget and environmental responses to stresses from the Long Point community updrift. However, as one of the principal mandates of a provincial park is to provide recreational facilities, these additional stresses are unavoidable. Park zoning, prohibiting unauthorized off-road vehicular traffic, and restricting camping and picnicking directly on foredune areas have all recognized the importance of restricting additional stress of high stress areas (i.e. the principle of **spatial variability).** Monitoring practices have also helped recognize the importance of limiting use of recently stressed or particularly sensitive areas.

Environmental studies for the park have recognized **stress cyclicity** relative to fluctuating water levels, while management plans have recognized that park facilities may be susceptible to erosion during high water levels. The dune stresses inherent in most recreational activities may also increase susceptibility to storm related stresses, in spite of attempts at mitigation. While encroachment on the nearby wetland meadow has been prevented by expanding the parking lot, no consideration has been given to whether the parking lot and channel associated with the boat launch might help induce inlet formation during extreme storm surge events on the back barrier.

While not explicitly recognizing **evolutionary change,** park policies have stated that new developments are not to be sited in areas where erosion may occur during their expected service lifetime. Alternatively, considerable attention has been given to controlling and/or mitigating the frequency of human stresses (i.e. **human stress control)** through zoning, controlling dune traffic, dune rehabilitation, as well as moving campsites from sensitive or recently stressed areas. Management practices such as maintaining and upgrading campsites have also attempted to limit environmental stress. Limiting stress frequencies has also been recognized by placing a moratorium on developing further campsites and development, despite increasing demands.

8. SIGNIFICANCE FOR MODELLING ENVIRONMENTAL STRESS

This research advances the theoretical basis of environmental assessment by modelling interactive ecological-human systems using stress-response concepts within a systems context, focusing on interactions in an abiotic environment. Advances in conceptualizing environmental stress-response complexities have been reviewed in ecology (e.g. Odum et *al.* 1979), including stress ecology (e.g. Bar-ret 1981; Pickett and White 1985), and landscape ecology (e.g. Godron and Formon 1983), and in geomorphology (e.g. Brunsden and Thornes 1979). Developments have been made in characterizing stress types, specifying spatial and temporal characteristics, and understanding system response.

The review of theory in systems analysis, ecology, and geomorphology has provided useful concepts for developing a conceptual integrative stress-response model which identifies key components and processes in an interactive ecological-human environment. Those most pertinent to this study, and arguably any stress-response model, include the principles of stress-dependency, stress frequency and recovery, environmental heterogeneity, spatial hierarchies and linkages, structural-functional response, and temporal change. In addition, specific concepts such as the eustress-distress dichotomy, usually considered in terms of biotic systems, have shown utility in modelling geomorphic systems as well.

As in other systems, categorizing stress-response in a sandy barrier environment is complicated by the hierarchical nature of subsystems, as stress effects may vary significantly at different system levels. Furthermore, the model has recognized the fundamental differences between human and natural stresses, based primarily on frequency-recovery relationships. For example, many human stresses were found to be cumulative rather than cyclical, not allowing natural recovery processes to increase the subsystem sediment storages that are crucial for stress resistance, resilience, and mitigation. In fact, extensive evidence exists to suggest that sandy barrier systems are better adapted to high magnitude washover events than cumulative human stresses such as shore protection.

The model developed in this study provides a technique to establish environmental management guidelines that represent current knowledge of barrier dynamics and ecosystems and is sensitive to the stress-regimes and environmental heterogeneity present at each barrier system and subsystem. The systems framework has proven to be helpful in recognizing that the effects of a perturbation may vary significantly at differing locations, and that stresses detrimental at one level or location can be beneficial at other levels or locations. The systems diagram was extremely useful in describing and portraying a hierarchy of interactions, including indirect sediment transfers and feedbacks. In addition, the systems diagram proved to be a valuable organizational, evaluative, and communicative tool, particularity in conceptualizing an environmental system in its entirety. In addition, the multi-stress nature of the signed digraph arrows have helped demonstrate the cumulative nature of both human and natural stresses, as well as synergistic and antagonistic interactions.

The model has also provided a means to organize ecological-human interactions and stress-response complexities which may have broader applicability to other environmental systems. There is much evidence to suggest that concepts of storage/linkage protection, stress-dependency, and environmental heterogeneity have applications far beyond barrier systems, including both biotic and abiotic systems. Furthermore, while only a select number of stress-response concepts were used in the model (e.g. eustress-distress, magnitude-frequency), both the model and the literature review illustrates that many stress-response terms are interdisciplinary. In fact, other traditionally biotic concepts such as species diversity may have abiotic equivalents (e.g. geodiversity), while system response trends (e.g. Bormann 1985) and ecosystem health indicators may also be developed for abiotic systems.

The model, in turn, has indicated the importance of dynamic stability, spatial integrity, and temporal heterogeneity for barrier stress-response, with particular emphasis on maintaining natural stress frequencies and sediment storages/linkages, while recognizing the roles of environmental heterogeneity and temporal change in modifying stress-response. These findings are not dissimilar to conclusions by other researchers. For example, many authors have emphasized the dynamic stability of barriers (e.g. Leatherman *et al.* 1978; Pilkey *et al.* 1980), while others (e.g. Riggs 1976; Nordstrom and Psuty 1983) have recognized the importance of dune storage for barrier stress mitigation. Sediment linkages have also been considered (e.g. Beard *et al.* 1991; Gares *et al.* 1980), while Nordstrom (1979) recognized the role of environmental heterogeneity by noting barrier beach response varies as a result of structures, offshore topography, and sediment supply. Nordstrom and Terich (1985) also recognized the principle of temporal change, noting that shoreline accretion should not be viewed as a permanent, irreversible process, and that periods of erosion and accretion are cyclic. However, this model is unique in its attempt to integrate many of these principles in a holistic, integrative stress-response framework, with the additional goal of providing the basis for developing management principles to assess how resource management policies recognize biophysical processes and related human stresses. The findings of the model and its evaluative principles may have great utility for sandy barrier management, as managers may use its findings to amend resource management policies, as well as assess the environmental impacts of proposed development or redevelopment in the park and other areas of Long Point.

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