NEARSHORE WAVE ENERGY

AND

BLUFF RECESSION RATES

ALONG LAKE MICHIGAN'S SOUTHEASTERN SHOREZONE

By

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A THESIS

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ABSTRACT

Bluff crest recession along the southeastern shore zone of Lake Michigan is examined coincident to wave energy probabilities associated with storms recurrent at 5, 10, 20, 50, and 100-year intervals. The investigation considers twenty three previously studied sites composed of unconsolidated sediments. Recession rates are based on measured crest retreat while wave energy values are derived through computation. Correlation and regression tests suggest that the total effect of relatively frequent storms of moderate intensity is morphologically more significant than that of rare, high energy events. Improved results may be possible with refinements in the experimental design.

To my brothers Ted and Eric

who have always challenged and inspired me.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

LITERATURE REVIEW, OBJECTIVES, AND METHODS

Introduction

Landowners spend millions of dollars annually to preserve lake front property. Even so, in 1986 record high levels on Lake Michigan brought high erosion rates and staggering economic losses. In response, Michigan allocated $12 million in low interest loans and community grants to aid areas of severe erosion in seventeen counties. During March, 104 applications were made to the Emergency Home Moving Program; sixty-three houses had already been certified "in imminent danger." By April an estimated 800 homes were within 20 feet of the waterline. Such threats to property and resulting high expenditures by the private sector and government agencies justify research to better understand coastal erosion.

The interaction of physical factors involving erosion along Lake Michigan's coastline is complex and not fully understood. The purpose of this study is to examine the relationship between long-term bluff erosion, storm intensity, and nearshore wave energy. Comparing the energy associated with severe fall and spring storm waves with long-term recession rates may help reveal and define interrelationships between these two factors.

Literature Review

The Lake Michigan coastline has interested investigators and authors since the late 1800s (Andrews 1870; Brater n.d.; Buckler 1981; Powers 1958). Numerous scientists have studied many different aspects of coastal processes. Recent research and publications on Great Lakes' shorezones demonstrate continuing interest in coastal phenomena, especially those contributing to erosion.

A variety of investigations reflects the complexity of the shoreline. Some observers have inventoried and described subaerial, physical attributes and geomorphic processes (Birkemeier 1981; Brater and Seibel 1973; Buckler 1973a, 1981; Buckler and Winters 1983; Davis 1976; Davis, Fingleton, and Pritchett 1975; Gilbert 1985; Powers 1958). Others have studied the subaqueous, nearshore environment with most concentrating on the formation and behavior of longshore bars (Hands 1976, 1980; Orme 1985). A sediment or volumetric balance is commonly considered in engineering-oriented studies (Davis n.d.; Hands 1980, 1981, 1984; U.S. Army Corps of Engineers 1986a, b, c, d, e). Other engineering studies focus on the structural protection of shorezones (U.S. Army Corps of Engineers 1984; 1986a, b, c, d, e). The use of vegetation as an inexpensive, natural means of erosion abatement is discussed by Clemens (1977) and Hall and Ludwig (1975).

Wave energy is considered a key factor in coastal zone modification. To better understand their climate and distribution, Liu (1970) and Liu and Housley (1970) presented some qualitative characteristics of waves from visual observations. Resio and Vincent (1976) rendered wave data based on a numerical hindcast model simulating storm-generated waves of varying intensity. Allender et al. (1981) and Paddock and Ditmars (1981) developed and tested numerical methods for modeling nearshore circulation and sediment transport. The advent of more advanced computer techniques has fostered interest in modeling the coastal environment numerically to simulate storm waves and evaluate designs that may mitigate coastal erosion (Allender et al. 1981; Allsop, Franco, and Hawks 1985; Paddock and Ditmars 1981).

Powers (1958) conducted a comprehensive study of Lake Michigan's shorezone in order to group coastal terrains based on type and association. He also determined some long-term recession rates by remeasuring distances coincident with section lines established by the original land survey conducted between 1820 and 1860. Powers resurveyed 134 section line locations; 23 of these are incorporated into this study.

Seven of Powers's points were reexamined in 1973 (Buckler 1973). During 1976 and 1977 many more were resurveyed (Buckler 1981; Buckler and Winters 1983) to examine the relationship between differential recession rates and selected physiographic characteristics. Buckler hypothesized that recession on the eastern shore exceeded that on the western shore--attributable to prevailing westerly winds and predominant easterly cyclonic passage. But he was unable to explain differential recession rates based on physical attributes; further, he found recession rates to be slightly greater along southern shores when compared to northern shores and relatively similar on both the east and west sides of the lake. Both Powers (1958) and Buckler (1981) include a summary of studies conducted as early as 1847.

A recent study of Thompson Island, Boston Harbor, Massachusetts (Jones, Fisher, and Reigler 1985) is similar to Buckler's investigations. Thompson Island, which is composed of unconsolidated Quaternary sediments (as is much of the Lake Michigan coast), was studied specifically to establish the relationship between beach erosion and seacliff recession considering various geologic and environmental factors. Jones, Fisher, and Reigler found that coarser-grained cliffs receded faster than finer-grained cliffs whereas Buckler (1981) and Buckler and Winters (1983) were unable to confirm a relationship between sediment size and bluff recession. The assertion that beaches oriented north and east would recede faster, because they are exposed to greater storm energy (similar to Buckler's hypothesis that the east shore receded faster than the west), could not be substantiated by Jones, Fisher, and Reigler.

Buckler's observation of higher recession rates toward the south may support speculation by Hands (1978a, 1978b) that accelerated southern shoreline retreat in Lake Michigan could be attributable to apparent coastal subsidence. This subsidence is actually submergence resulting from a continuing crustal rebound of the Lake Michigan basin, which began near the end of Pleistocene glaciation. Hands demonstrated with geodetic survey and lake level data that the northern portion of the basin is rebounding faster than the southern region, effecting an emerging coastline in the north and a submerging coastline in the south.

Hands (1976, 1980, 1981, 1984) further investigated the consequences of submerging coastlines using fluctuating levels on Lake Michigan as a surrogate to rising sea level conditions. Longshore bars were shown to migrate landward while maintaining constant depths beneath the gradually rising lake surface (Hands 1980). Testing and refinement of the Brunn rule led to development of sediment and volumetric balance procedures (Hands 1980, 1981, 1984). That is, a rise in mean surface elevation tends to shift the equilibrium profile landward. Eroded material from the upper beach supplies materials to build up the lower profile (beneath the water level). The method predicts long-term profile adjustments under rising level conditions based on an empirically verified model.

A recent investigation of longshore bars by Orme (1985) demonstrated the existence of stationary and nonstationary longshore bars on the Ventura, California, coast. Orme indicated that stationary bars are strongly associated with the breaker zone, the location of which in turn reflects wave steepness, nearshore slope, and tidal stage. Nonstationary bars are generally asymmetric and move landward over several days to a few weeks before they are destroyed by a changing wave climate or accumulating sediment to the point of instability.

A number of investigations were conducted in the early to middle 1970s during a period of unusually high lake levels (Birkemeier 1981; Brater n.d.; Brater and Seibel 1973; Brater, Armstrong, and McGill 1975; Davis 1976; Davis, Fingleton, and Pritchett 1975). These studies all incorporate an engineering approach that evaluated the relationship between several factors influencing erosion. Attributes commonly analyzed were lake level fluctuation, storm frequency, sediment transport/littoral drift, protective structures, slope stability, and grain size. The studies, up to three years in length, varied in duration and involved up to seventeen sites along the eastern shore of Lake Michigan. Most of the reports have similar findings. Recession rates are proven to vary at different locations along the coast but are apparently unrelated to bluff height or composition although bluffs with a high clay content are generally thought to be more cohesive and able to support steeper slopes (Brater and Seibel 1973).

Clemens (1977) and Hall and Ludwig (1975) reported on the use of vegetation to moderate shore erosion. They concluded that vegetation alone would not protect against wave-induced erosion. Vegetation is best used on barren areas to stabilize unconsolidated soils by reducing surface runoff and destructive aeolian processes.

High lake levels decrease beach widths and allow wave action to reach the base of bluffs and dunes, thereby accelerating erosion rates. Some investigators speculate about the relationship between erosion rates and various factors influencing wave energy; however, they present no quantitative evidence to support their claims. The interrelationship of varying fetch distances and depths with shore juxtaposition to storm wave climate and cyclonic movement across Lake Michigan is also discussed empirically in some studies. There is abundant evidence linking the most damaging erosion events with high energy storms, but not mean wave activity.

Much has been written on both wave and storm characteristics and their combined effect on the Great Lakes shorezone (Birkemeier 1981; Brater and Seibel 1973; Buckler 1981; Buckler and Winters 1983; Davis 1976; Davis, Fingleton, and Pritchett 1975; Gilbert 1986; Hands 1976, 1980; Powers 1958). There is a general consensus that major erosion events are produced by high energy storms, as well as an acknowledged relationship between high water elevations and accelerated erosion rates. Wave properties are even more dynamic than the shoreline conditions, but they are more difficult to measure and observe quantitatively. Liu (1970) and Liu and Housley (1970) presented a summary of visual wave observations for Lake Michigan compiled during two consecutive autumns in 1966-1967 and one autumn in 1965, respectively. They observed greater wave heights along the northern shore and longer wave periods to the south. At the time of his study, Liu (1970) noted that theoretical models showed little quantitative agreement with observed waves.

Hindcasting is a means of calculating past wave characteristics using historic synoptic wind charts. In 1976 Resio and Vincent *hindcasted* wave information for 64 points along the Lake Michigan shoreline. To do this, they used a model developed primarily by Barnett at the Scripps Institute of Oceanography which uses a theoretical representation of energy transfer mechanisms to compute energy spectra at grid points. The Resio and Vincent model yields significant wave heights and periods for severe storms with probable return periods of 5, 10, 20, 50, and 100 years. Their model further subdivides the information for spring, summer, fall, and winter storms.

More recently, Paddock and Ditmars (1981) and Allender et al. (1981) developed and tested numerical models to evaluate nearshore coastal processes. In general, they conclude that the nearshore wave environment is hydraulically complex and further complicated by longshore bars. Although numerically feasible, the Paddock and Ditmars (1981) model is constrained by an enormous computer requirement which makes it impractical to simulate more than a few minutes of activity. The model developed by Allender et al. (1981) seems to underestimate wave height decay within the breaker zone which is believed attributable to inadequate representation of wave behavior in the region of bar-trough topography.

The Michigan Department of Natural Resources has classified the Michigan shoreline as either high risk erosion areas, flood risk areas, or environmentally sensitive areas (Michigan Division of Land Resource Programs 1982). Classification of high risk erosion areas is accomplished by comparing historic and recent aerial photos and extensive field survey. Areas are designated as *high risk* if their average, long-term recession rate (determined photogrametrically over a period of twenty to forty years) exceeds 1 foot per year. High risk erosion areas are then subject to management and zoning, emphasizing a nonstructural approach. The program is primarily an administrative policy which requires set back distances, from the bluff line, to protect new construction or improvements to existing structures.

The U.S. Army Corps of Engineers maintains several harbor structures along the eastern shore of Lake Michigan. Section 111 of the River and Harbor Act of 1968 authorizes the investigation and construction of projects to prevent or mitigate shore damages resulting from federal navigation works (Larson 1981). Under the provisions of Section 111, the Detroit District (U.S. Army Corps of Engineers) monitors shorezone reaches north and south of their harbor projects to evaluate ongoing beach nourishment efforts designed to moderate erosion induced by structural blockage of littoral drift (Larson 1981; U.S. Army Corps of Engineers 1986a, b, c, d, e). Their reports address the extent of coast affected by harbor jetties, present volume balance estimates, percentage of total coastal erosion directly attributable to Corps-administered works, and an appraisal of beach nourishment effectiveness.

In summary, these references confirm the complex nature of shorezone interactions and erosion. More specifically, these studies recognize the influence of several factors contributing to different recession rates including nearshore topography, storm frequency and intensity, vegetation, structures, lake level, and wave climate.

The relationship between available wave energy and rates of bluff recession has often been asserted but seldom investigated in detail. It is possible that heterogeneous wave energies may account for different bluff recession rates, and that is the focus of this study. If so, this relationship could be useful in further understanding the dynamics of coastal morphology and guiding future shorezone management decisions.

Objectives and Hypothesis

The objectives of this study are

1. To reexamine sites previously used to determine long-term bluff recession (Powers 1958; Buckler 1981) that coincide with shore reaches monitored annually by aerial photography (U.S. Army Corps of Engineers 1986a, b, c, d, e). And to update long-term bluff recession rates for selected sites along the eastern shore of Lake Michigan, from St. Joseph to White Lake, Michigan.

2. To examine the hypothesis that recession rates at those sites are positively related to nearshore wave energy associated with storm events. The hypothesis is a deduction based on the following observations: (a) Shorezone erosion is frequently attributed to wave action during high energy fall and spring cyclonic storms (Brater and Seibel 1973; Birkemeier 1981; Davis, Fingleton, and Pritchett 1975; Hands 1980). (b) Bluff recession rates vary at different locations along the coast but are apparently not related primarily to shore composition or physiography (Buckler 1981; Buckler and Winters 1983). (c) Because development of deep water waves depends on wind velocity and duration combined with fetch and depth, the wave energy varies at different locations along the shore (Resio and Vincent 1976). Therefore, it is possible that nearshore attenuation of deep water wave energy may partially explain differential bluff recession rates.

Study Area

The study area encompasses a portion of shoreline along the west coast of southern Michigan between St. Joseph, in the south, to White Lake, in the north (Figure 1). The shorezone consists of unconsolidated Quaternary sediments.

General Criteria

The intersection of some U.S. Public Land Survey section lines with the Lake Michigan bluff line provides a means for determining long-term bluff recession. A record of the distance between bluff crest and the nearest section corner is contained in the original General Land Office (GLO) survey notes (1827-1852). By comparing the distance established in the GLO survey with a recently measured distance, over the same transect, long-term recession rates can be calculated. Furthermore, several of these sites were resurveyed within the last thirty years by both Powers (1958) and Buckler (1981), providing an opportunity to determine short-term recession data.

Deep water wave heights and periods are given for similar locations along the Lake Michigan coast by Resio and Vincent (1976) (Figure 3 and Appendix A, Tables 6 and 7). The data are numerically generated and tabulated for seasonal wave values associated with storms of 5, 10, 20, 50, and 100 year return periods. Breaking wave energies are calculated with solitary and linear wave theories using data from the Resio / Vincent model.

The two data sets, long-term bluff recession and nearshore wave energy, can be compared statistically. The amount of variance in recession rates accounted for by storm intensity wave energy can be discerned with correlation and regression testing.

The General Land Office Surveys

The first governmental surveys of Michigan, conducted between 1827 and 1852 by the General Land Office (GLO), may constitute the oldest, reliable, quantitative record for the Lake Michigan shoreline. Consistent with the U.S. Public Land Survey system, Michigan is divided into townships, generally 36 miles square and 6 miles on a side. Each township is further subdivided into 36 sections, 1 mile on each side. The Michigan meridian, or principal meridian, is located approximately 6 miles east of East Lansing, Michigan and provides one basis for surveying boundaries of townships and extending the grid system to the Lake Michigan shore. The partitioning ends at the last full section or quarter section grid adjacent to the lake. The remaining distance from the last section corner (or quarter corner) to the "meander line" is recorded in the GLO notes. Powers (1958, p. 89-90) observes, "the 'meander line' was never precisely defined, but clearly it was seldom, if ever, identified as the water line. In many cases the measurements were obviously made to some point at or near the edge of the bluff, where present." Measurements of questionable accuracy were eliminated by both Powers and Buckler to maximize reliability. This study utilized data from sites where successive surveys were judged to be precise and correct.

The Buckler Study

Buckler (1981) reexamined Michigan sections, in the original GLO survey, searching for remeasurable township lines that intersected shorezone bluffs. Buckler refined the data by eliminating sites that did not meet this criterion as well as those with a "questionable relationship between the meander line and the bluff crest" (Buckler 1981, p. 6). Buckler's work identifies numerous sites in Michigan suitable for studying long-term bluff recession.

The Section 111 Studies

The U.S. Army Corps of Engineers, in compliance with Section 111 of the River and Harbor Act of 1968, monitors nearshore processes in the vicinity of their Lake Michigan harbor structures (Figure 2). Annual measurements include bathymetric soundings and observations from current aerial photographs. Several sites identified in Buckler's work are also covered by this aerial photography, which extends several miles north and south of each harbor project. This circumstance makes it possible to observe annual changes at some sites where long-term recession rates are known.

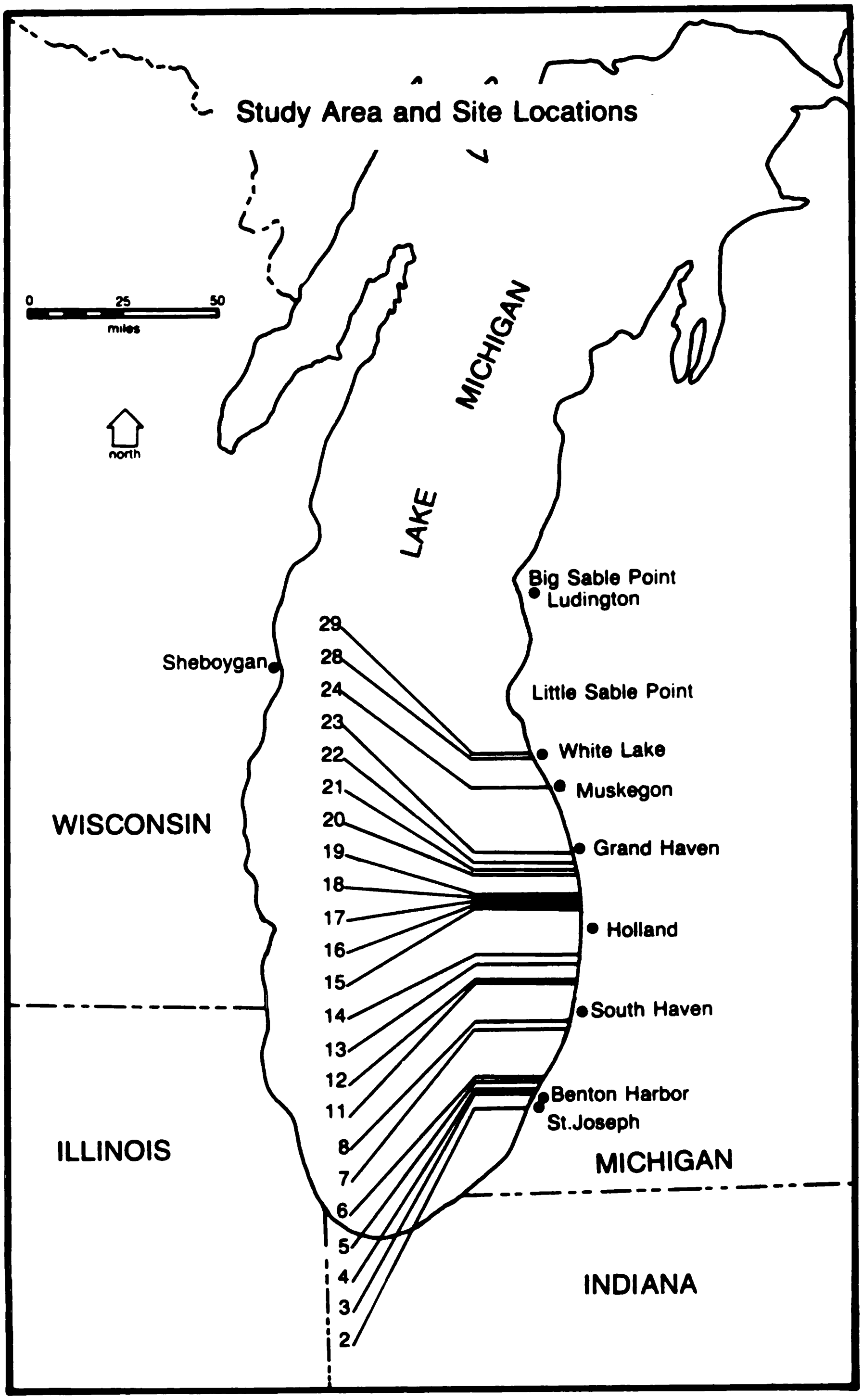


Figure 1. Study areas and site locations.

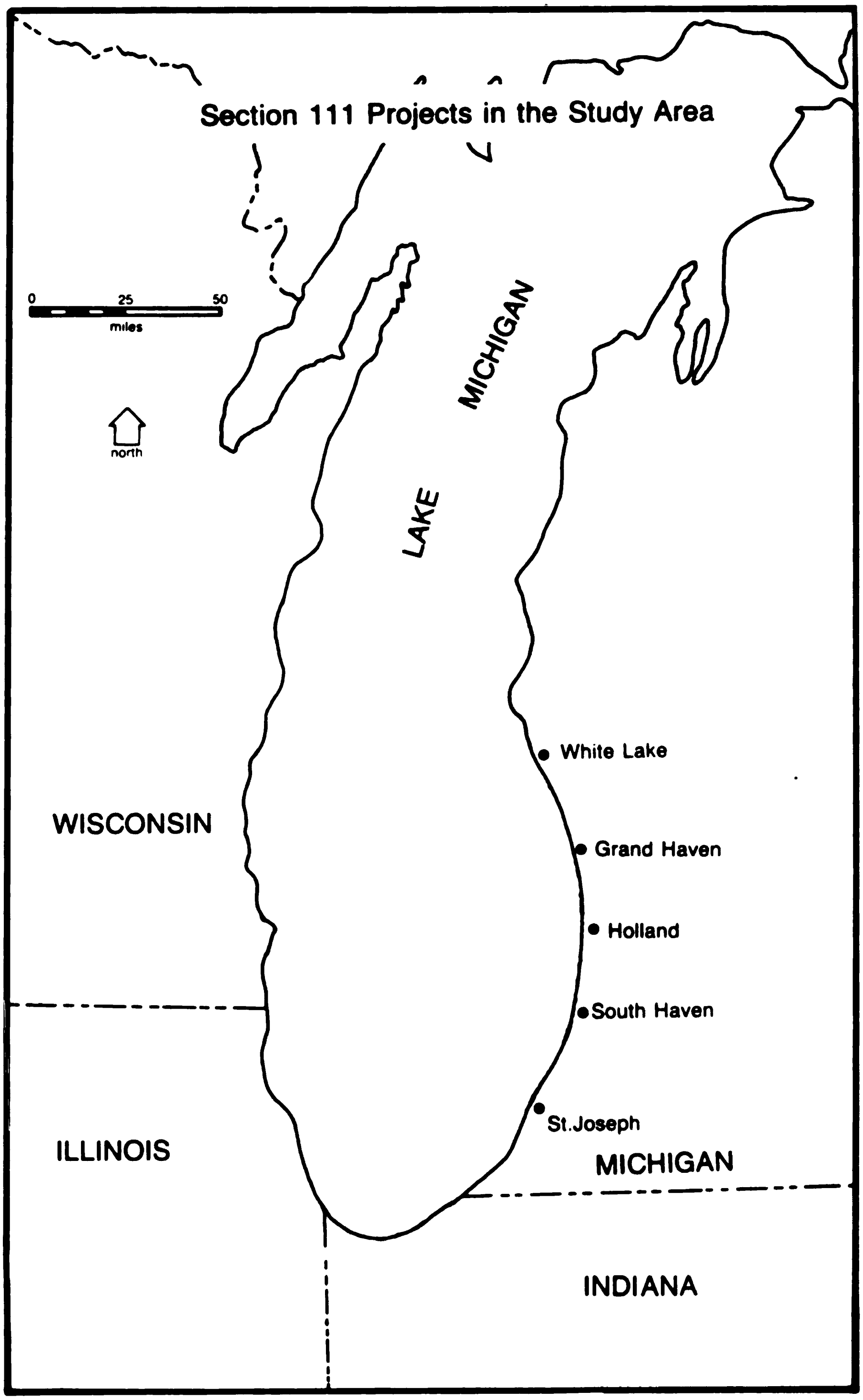


Figure 2. Section 111 project locations.

Site Selection Criteria

Twenty sites from Buckler's 1981 study are in the area monitored by the Corps of Engineers, and all but one are included in this study. The one site (M-38) was eliminated because of its isolated northern location several miles from the other 19 sites clustered south of Little Sable point. In addition, sites M-11 to M-14 previously measured by Powers (1958) and Buckler (1981) were added to provide a continuity of sampling points between St. Joseph and White Lake, even though they are not within the area of Corps of Engineers aerial photographs.

Each of these sites represents the intersection of a section line with a shorezone bluff known to have experienced recession. Bluff definition and measurement are described by Buckler (1981, p. 5):

> A bluff is defined as a lakeward-facing steep bank or sharp slope composed of unconsolidated material landward of the shoreline. Bluff crests provide reliable standardized lines to which measurements can be made. Water lines are less acceptable because the surface altitude of Lake Michigan fluctuates to a considerable degree.
>
> Measurements of bluff change refer to the landward displacement or lakeward accretion of the *top edge* of the bluffs. It should be recognized, however, that changes may take place on the bluff slope that do not necessarily affect the position of the crest.

With only one exception, none of the sites are directly fronted by a protective structure. The protected site, M-2, has been fortified with heavy rock armor at the water line. The long-term recession value used for M-2 was calculated by Buckler (1981) prior to placement of the revetment.

Measurement Procedures

Except for locations M-11 to M-14, which were examined in the field using standard surveying techniques, distances at sites M-2 to M-23 were measured from photographs taken in April 1986. Sites M-24, M-28, and M-29 were examined from photography dated April 1985. All aerial photographs were obtained from the Detroit District, U.S. Army Corps of Engineers and have an unrectified approximate scale of 1:6,000.

The true scale of each photograph was calculated by determining the distance between two points of known separation. By comparing the actual ground distance between the points to the length measured on the photograph, the scale can be determined. The location of section and quarter corners is revealed by the intersection of certain linear cultural features and/or boundary markers. This procedure is consistent with techniques described by Powers (1958, p. 90):

> In no case was an original corner or quarter post recovered, but the position of long established fence lines and other boundary indications checked closely with the chained distances given in the original survey. It is believed that most if not all points of origin used for remeasurement were correct to within 3 to 5 feet of their true position.

And followed by Buckler (1981, p. 7):

> In a few cases where records were lacking and field monuments could not be found it was possible to determine section corner locations by fence and road patterns fairly accurately (within three to five feet).

Where the corner or quarter corner was not obvious, an intermediate landmark was used. In several cases the remaining distance between a road intersection to the corner of interest had already been measured either by Buckler or registered land surveyors. Summing the measures to the intervening control point yielded the total distance of interest. The estimated accuracy of identifying points of origin on the aerial photography, under magnification, is .01 inch; at a scale of 1:6,000 this translates to a possible ground error of 5 feet.

The distance from most section corners or quarter corners to the bluff crest was then measured along the section line, which is often easily identifiable as a fence row or road center line. Where there were no linear features marking the section line, measurement was made due west to the bluff line.

The bluff crest is defined as "the point or line of abrupt change in slope at the top of the bluff" (Buckler 1981, p. 143). Stereopairs of aerial photographs were used to identify the location of the bluff crest along selected section lines. At places where the crest is notched by human disturbance, projecting an imaginary line connecting the bluff edge on either side of the site inferred the natural position of the crest.

Distance on the aerial photography was measured with a TEKTRONIX 4956 digital graphics tablet to 0.005 inch (manufacturers specified resolution). Each length was measured three times; an average of the three measurements constituted the accepted value. Assuming the final value is accurately measured to 0.005 inch, the error on a 1:6,000 scale photograph is plus or minus 2.5 foot.

To establish a control for photo-interpretation accuracy, 20% of the sites were also measured in the field using the same criteria. Distance was measured with a 100 foot steel tape and surveyor's compass utilizing standard surveying procedures as described by Kissam (1971). Comparing the ground measured distance to that calculated from the aerial photographs yields an accuracy within 1.2% or an average of eight feet.

Wave Energy Estimation

Deep water wave data are given by Resio and Vincent (1976) from a model designed to calculate significant wave heights and periods for waves generated by synoptic-scale systems, such as extratropical storms. *Significant* wave height is defined as "the average of the one-third highest waves in an observation period and was intended to correspond to that wave height estimated visually by an observer." *Deep water* refers to the depth that waves are unconstrained by frictional lake bottom influence usually defined as one-half the deep water wave length ($L_o/2$). The accuracy of waves projected by the model is described by Resio and Vincent (1976, p. 32):

> The agreement between hindcast wave maxima and observed wave maxima for cases involving fetches over 20 miles and for wave propagation toward shore was extremely good. All the hindcast maxima were within 1.5 feet of observed maxima. The root-mean-square error in estimating peak wave heights for this set of conditions is about 1 foot.

Resio and Vincent provide wave statistics at 64 locations on Lake Michigan (Figure 3). Points 16 through 26 are used in this study. Values for specific study sites, between points where wave data are given, are calculated by linear interpolation. Fall and spring values for waves approaching obliquely and parallel to the shore are considered in this study. Periods associated with the wave heights are given as the average across all possible angles (of incidence to the shore) that correspond to the particular wave height (Sam Corson 1986, personal communication).

Breaking wave height (H_b) and mean energy flux are calculated using the computer program SINWAVES (MACE-11) for linear wave theory predictions (U.S. Army Corps of Engineers 1985). The program applies Snell's law of refraction (U.S. Army Corps of Engineers 1984, p. 2-64) to calculate the refraction coefficient, assuming straight and parallel bottom contours. This assumption is a good approximation of the nearshore bathymetry throughout the study area and is consistent with procedures used in recent Section 111 studies (U.S. Army Corps of Engineers 1986a, b, c, d, e). Wavelengths are evaluated at different depths using a subroutine that solves the linear dispersion equation by iteration. Breaking height and depth are also determined by iteration using equations 2-92, 2-93, and 2-94 (a modified solitary wave theory) from the *Shore Protection Manual* (U.S. Army Corps of Engineers 1984, p. 2-130) and the above mentioned wavelength subroutine. This process assumes that linear wave theory applies up to the point of breaking (U.S. Army Corps of Engineers 1985).

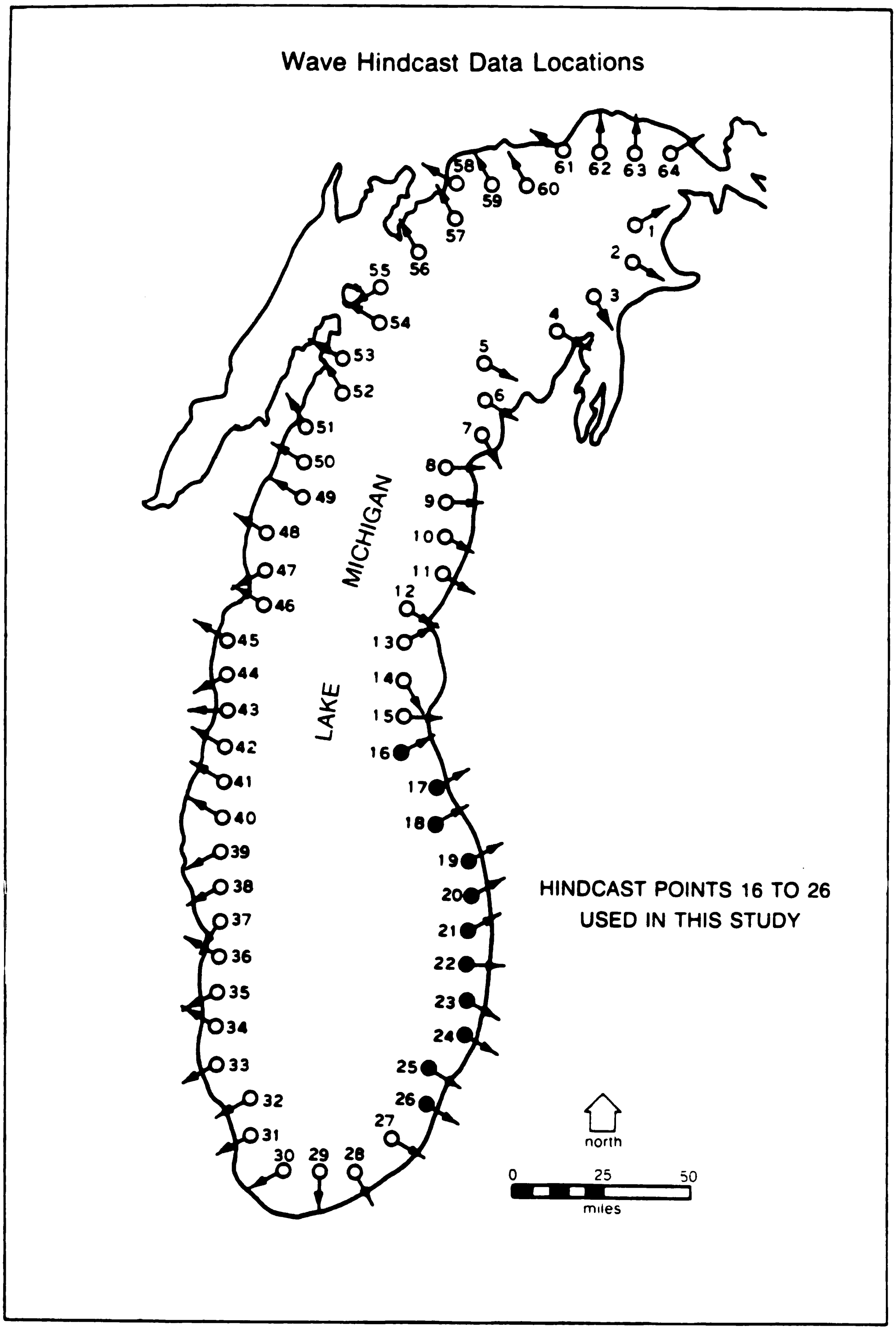


Figure 3. Locations of grid points for two-dimensional deep water wave spectra. From Resio and Vincent 1976.

Estimating nearshore wave energy requires an approximation of shorezone bathymetric slope in addition to values for deep water wave height and period. The nearshore slope is estimated on the basis of data from the U.S. Army Corps of Engineers, Section 111 studies and information from certain 7.5 minute U.S. Geological Survey topographic maps. Detailed bathymetric surveys are conducted annually as part of the Section 111 studies. Transects run orthogonally from the shoreline and record bottom variations at 1 foot intervals to a depth of 30 feet. Slope is calculated using elevation values from the shore and the 30-foot depth. This procedure, which normalizes nearshore topography, is necessary because the SINWAVES program cannot accommodate wave behavior in the longshore bar complex. At study sites where Section 111 survey data are unavailable, the slopes are estimated from U.S. Geological Survey, 7.5 minute topographic maps which record contour intervals to the 30-foot depth.

Chapter 2

SHOREZONE CHARACTERISTICS AND COASTAL PROCESSES

Introduction

Of the Great Lakes, Lake Michigan is second only to Lake Superior in water volume -- 1,181 cubic miles. It is the third largest of the Great Lakes in terms of surface area, 22,300 square miles, and mean depth of 279 feet. The lake's maximum 118-mile width spans 3° of longitude from 85° west to 88° west. It is 306 miles long, spanning about 4° of latitude from not quite 42° north to 46° north. At this latitude Lake Michigan is in the westerly wind belt and subject to cyclonic storms that may generate vigorous wave action along its 1,362-mile coast.

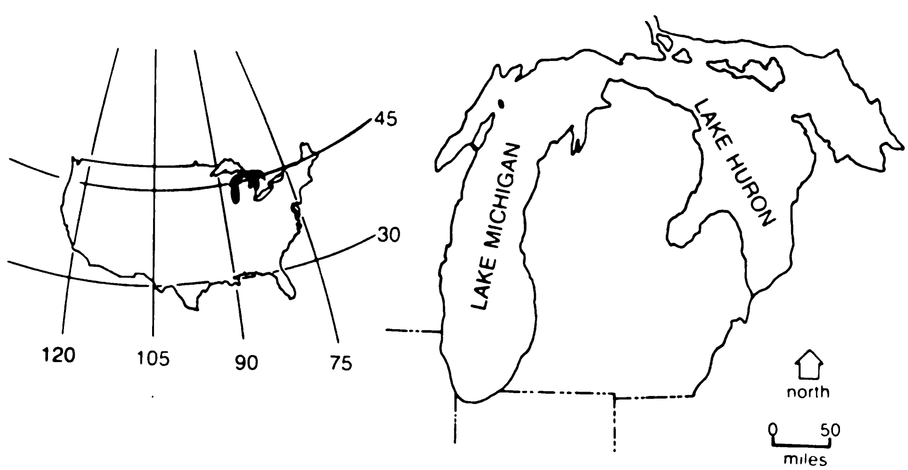


Figure 4. Location map for the Great Lakes.

Varying precipitation and evaporation rates impart both seasonal and annual lake-level fluctuations. Coastal erosion is generally most severe during periods of high lake levels when the beaches are narrow or nonexistent. Under these circumstances, the unconsolidated, Quaternary sediments that comprise the shorezone may be eroded directly by storm waves.

Terminology

Terminology used in this study is defined in the glossary of terms and graphically represented in Figure 5.

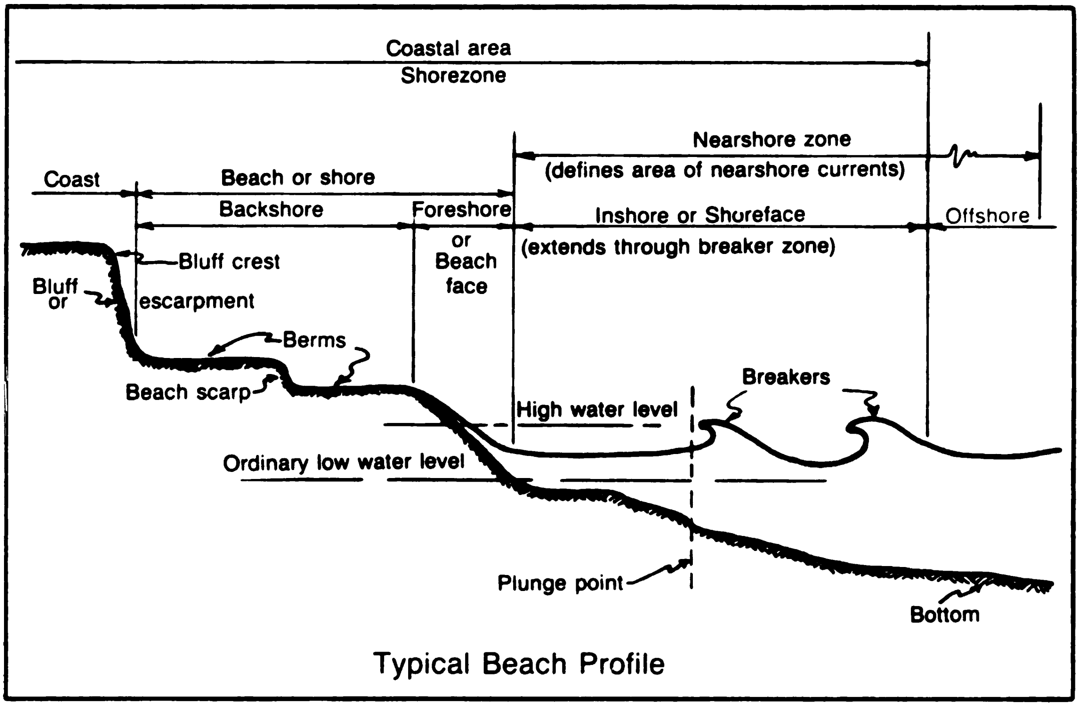


Figure 5. Visual definition of terms describing a typical beach profile.

Shorezone Characteristics

The shorezone in the study area is composed entirely of low to high banks of unconsolidated Quaternary sediments. Bedrock is not exposed anywhere in the study area. Sediments are primarily glacial drift, eolian sand, and postglacial lacustrine and stream deposits. Several investigators have discussed the relation of this material to erosion rates (Birkemeier 1981; Brater and Seibel 1973; Buckler 1973a, 1981; Buckler and Winters 1983; Davis 1976; Hall and Ludwig 1975; among others).

In some areas, the bluffs are composed of one sediment type, while in others there may be an intricate mosaic of interbedded, stratigraphic layers. At some places a combination of permeable glacial-fluvial sediments comingled with relatively impermeable till or lacustrine clays forms perched water tables and affects ground water flow, possibly causing seepage on the bluff face.

Dune topography varies from that of low relief to heights exceeding 150 feet. Dunal tracts may be a mile in width and extend several miles along the coast. Elsewhere, bluffs constructed of cohesive till stand very steeply over of 100 feet high.

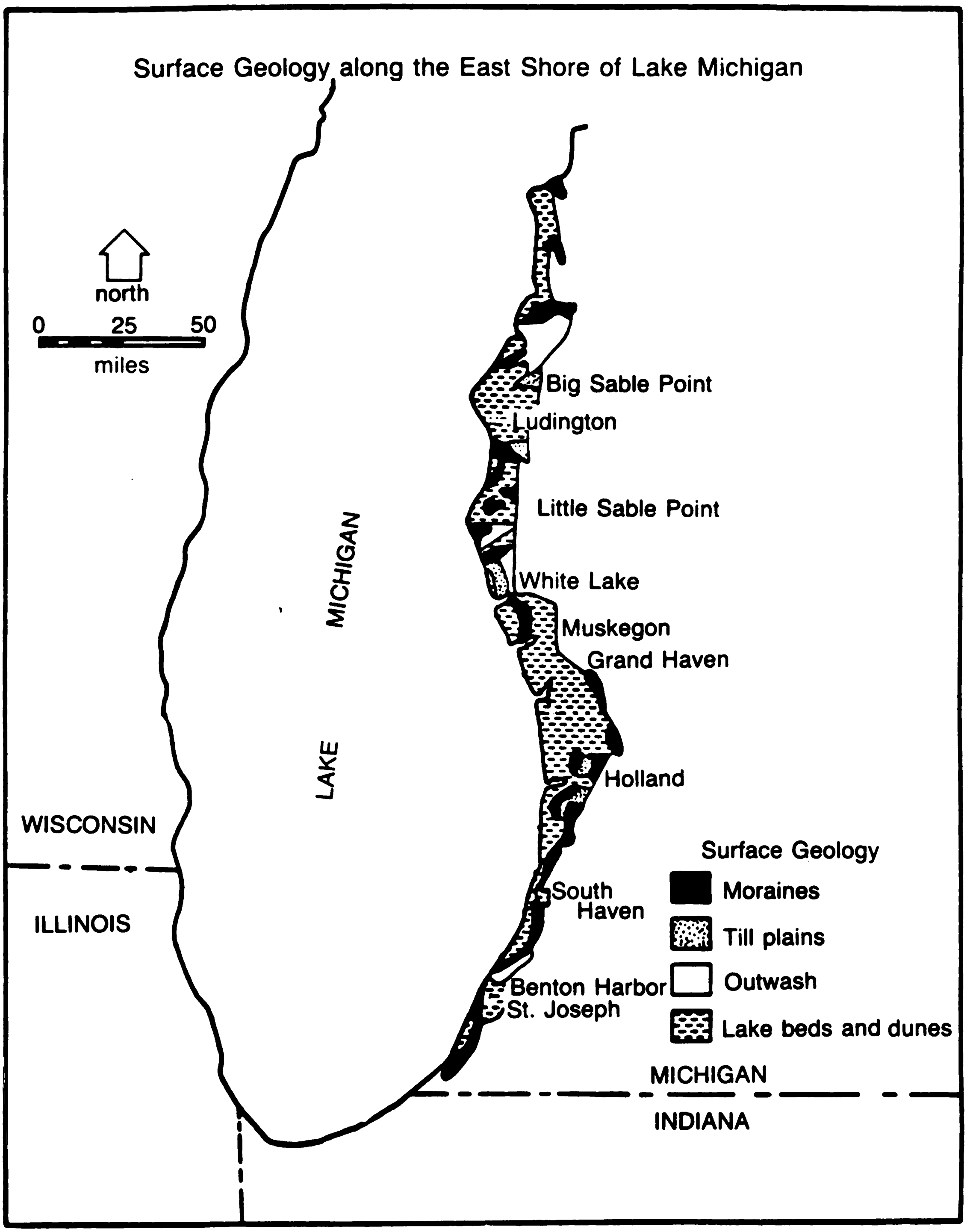


Figure 6. Map showing variations in surficial formations along the east shore of Lake Michigan. After Davis 1976.

Beaches

The character of Lake Michigan beaches is highly variable and subject to several influences including wave climate, lake level, littoral drift, and shorezone physiography. Furthermore, and especially during times of low lake level, wide, sandy beaches contribute fine-grained eolian material to the landward shorezone. Fore dunes may develop from ordinary beach sediments or ephemeral sand bars that are successively pushed ashore to accrete on the beach (Davis 1976; Gilbert 1986; Hands 1984). Conversely, when lake levels are high, beaches are narrow or even absent, limiting the supply of eolian sand.

Beaches react in basically two modes to wave motion: a response to typical waves and in adjustment to storm conditions. Under normal circumstances, wave energy dissipates largely along and across the beach. In some cases, generally in the summer, an ephemeral bar may form close to shore and migrate onto the beach to become part of the beach; this seems to provide limited protection to the backshore during future storms.

High energy storm waves, however, may evoke extraordinary changes. These large waves reach farther into the backshore, and their correspondingly higher energy can move larger-sized particles by both traction and suspension. Storms may also increase the capacity of the littoral current to transport more sediment because higher waves widen the transport zone offshore. Consequently, during severe storms, large sections of beach and dune can be lost. In time the beach may recover, but usually not without permanent bluff recession.

Longshore Bars

Longshore bars are a sequence of submerged offshore sand ridges, parallel to the strand line, in the nearshore zone. The there may be as many as five in places. Numerous investigators have reported on longshore bars (Allender et al. 1981; Davis, Fingleton, and Pritchett 1975; Gilbert 1986; Hands 1976, 1978b, 1980, 1984; Orme 1985; among others). According to the U.S. Army Corps of Engineers (1986a),

> In areas where there is a supply of transferable material, the existence of well developed longshore bars is an indicator of sediment available for movement in the nearshore transport system. The absence of such bars generally indicates a disequilibrium and a nearshore sediment deficit.

Hands (1984) showed that when lake levels are rising, the entire bar complex migrates toward shore while maintaining constant depths beneath the lake surface. The bars seem to be stable during storms, although Davis (1976) believes that they may be modified by high amplitude waves during the storm and return to equilibrium, with no apparent changes, as the storm subsides. Wave dynamics in this zone are extremely complex and little understood--linear wave theory is not applicable in the ridge and runnel topography. During storms, waves break on all bars in a multiple bar system, the largest waves breaking on the deepest bar and progressively smaller breakers occurring on the inner bars. The waves which finally reach the shoreline are thus reduced in size. When smaller waves prevail, they pass over the deep bars and do not break until they reach the shallow water over the inner bar (Komar 1976).

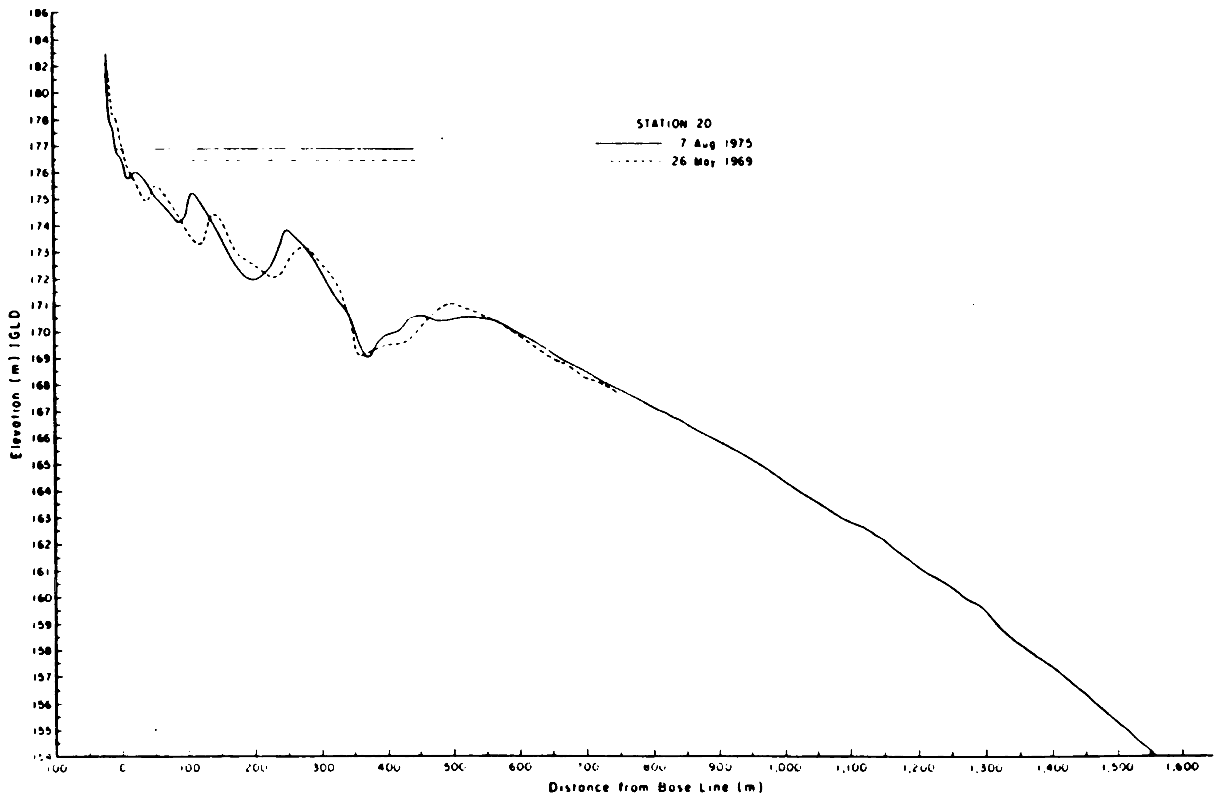


Figure 7. Longshore bar profile under rising lake level. From Hands 1980.

Bathymetry

Lake Michigan can be divided into four bathymetric regions: a southern, central, and northeastern basin, and Green Bay. The study area is along the eastern edge of the southern basin, which extends from the southern shore to a rise that crosses beneath the lake between Sheboygan, Wisconsin and Ludington, Michigan. This ridge is thought to be one or more submerged moraines of the Lake Michigan glacial lobe (Powers 1958). The deepest part of the southern basin is mid-lake, west of Holland, Michigan, where the maximum depth ranges from 490 to 650 feet. Water depths gradually decrease along relatively smooth bottom profiles shoreward of the mid-basin area. Bathymetry is a relatively important dimension when considering erosion. Basin topography and shoreline geometry govern wave development, by limiting depth and fetch, and are also linked to ice formation and break up.

Lake Level Fluctuations

The level of Lake Michigan is always changing; fluctuations may be measured in hours, seasons, decades, or in terms of geologic time. Lake Michigan's elevation vacillates because of natural forces. Variation in lake level is the product of several factors and is manifested in three noticeable regimes superimposed on one another. Short-term fluctuations are attributable to meteorological phenomena, and not volumetric change. Contrasting barometric pressures over different lake locations or strong winds can, in effect, tilt the lake surface, causing locally higher levels in one area and correspondingly lower levels simultaneously elsewhere. Annual variations on the order of 1.1 feet are predictably cyclic. Changes in precipitation, evaporation, and runoff raise Lake Michigan to a yearly high about July or August and subsequent low around December or January.

Longer-term Holocene fluctuations are the major concern of coastal inhabitants. Since lake level monitoring began around the middle 1800s, Lake Michigan has varied nearly 6 feet in elevation (Figure 8). This is particularly significant since a 1-foot rise in elevation can decrease beach width by an average 20 feet.

Longer-term variations largely reflect climatic trends in precipitation throughout the Lake Michigan/Huron drainage basin over several years (Buckler 1973b; Harris 1986). Lake Michigan and Lake Huron are hydraulically a single unit. A deep, wide channel at the Straits of Mackinac connects the two. Levels of the entire Great Lakes system remain predominantly self-regulated despite artificial outlets and diversions. "Under natural outlet conditions, the lake's levels and outflows adjust continually to maintain a balance between the quantity of water supplied to it and the quantity of water leaving it" (Harris 1986).

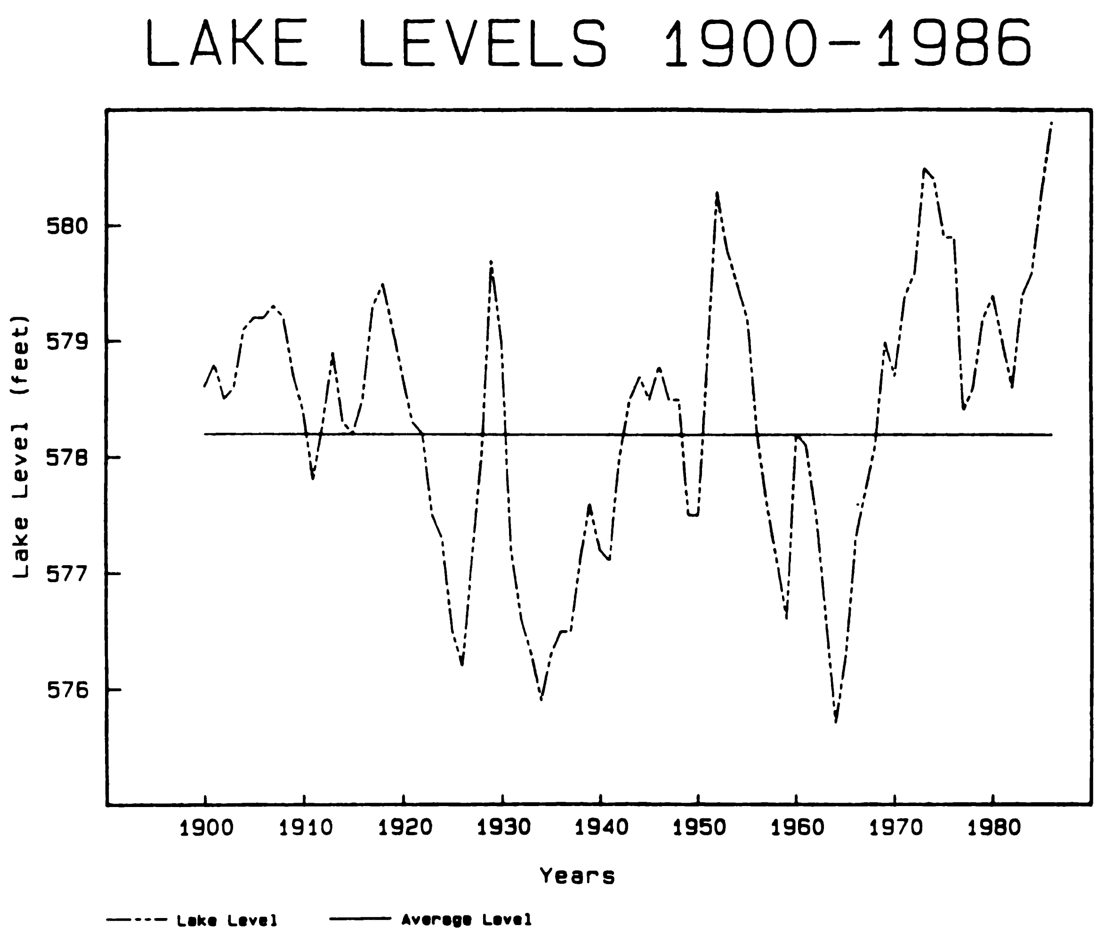


Figure 8. Long-term average annual water levels of Lake Michigan.

In the context of geologic time, there has been considerable fluctuation in the level of Lake Michigan. Largely a result of Pleistocene glacial events, the most common evidence of former lake stages is sand or gravel beach deposits, similar to beaches of the present Lake Michigan but lying inland from them at a higher altitude (Hough 1958). At least 12 stages of Lake Michigan have been proposed with elevations ranging from 230 to 640 feet above sea level.

Numerous investigators have noted the connection between high lake levels and accelerated erosion rates (Birkemeier 1981; Brater and Seibel 1973; Brater, Armstrong, and McGill 1975; Davis 1976; Davis, Fingleton, and Pritchett 1975; Hall and Ludwig 1975; Hands 1981, 1984; among others). Although high lake levels accelerate erosion, the bluffs may also erode during periods of record low levels (Brater n.d.). Davis (1976) asserted that a mean annual elevation of 580.0 feet is a threshold above which erosion on Lake Michigan is universal. Cohn and Robinson, in an attempt to predict lake elevations, determined prominent cycles of 1, 8, 11, 22, and 36 years through a Fourier analysis of historic records between 1860 and 1970 (110 years) (Birkemeier 1981). Predictions by this method, however, have not proven viable because either the system is not cyclic or a complete cycle has not yet been recorded. The intricacies of this vast system are not fully understood. Predictions of lake level fluctuation are generally considered only on a yearly basis by observing watershed catchment and runoff. At present predictions beyond a year or more into the future are not reliable.

Waves

The effects of water waves are of paramount importance in coastal morphology. Waves accumulate wind energy, which is then transformed into fluid motion. Most wave energy is ultimately attenuated in the nearshore region, where it shapes the geometry and composition of the beach.

Wave magnitude is a function of wind velocity and duration. Wind duration is governed both by the duration of a certain significant wind speed and by the available distance across open water (fetch). Both wave height and period on Lake Michigan are limited by fetch. Regardless how great the velocity, there is only a finite distance that the wind can blow across an open water surface. Average Lake Michigan fetches are from 70 to 100 miles. Given these distances and using the SMB method (Sverdrup, Munk, and Bretschneider), a sustained 30 knot wind over 7 hours can produce 5-foot waves in deep water; a 40-knot wind, of comparable duration, would generate 14-foot, deep water waves.

Waves affect sediment in three ways that, in turn, influence shore erosion and beach profiles: 1. waves that approach the shore obliquely create longshore currents and corresponding sediment transport; 2. breaking wave turbulence suspends some bottom sediments; and 3. orbital motions in the wave forms move sediment back and forth in a wide band, offshore beyond the breaker zone (King 1959). The depth at which waves effect bed motion depends on both wave height and length (Figure 9).

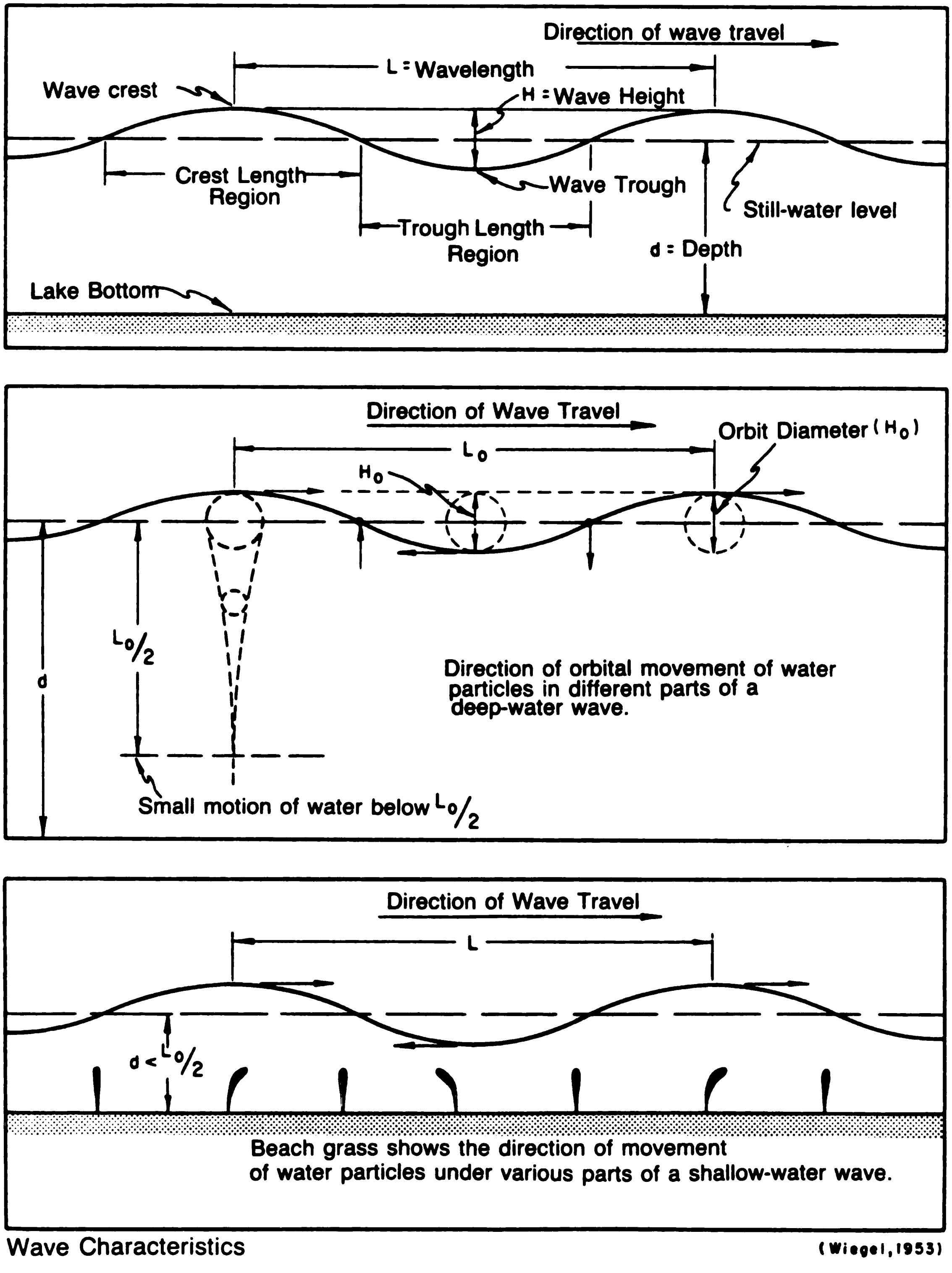


Figure 9. Wave characteristics and direction of water particle movement. From the *Shore Protection Manual*.

The deeper the water, the lower the wave bottom velocity. According to linear wave theory for a deep water wave ($L_o/2$), the bottom orbital velocity is approximately 4% of surface velocity.

Waves may travel hundreds of miles before reaching the coast. As a wave moves progressively toward shallower depths, the bottom eventually imparts a frictional drag on the wave, causing it to slow, steepen, and eventually break (Figure 10). Waves that break on the outer bars often reorganize to break again closer to shore. After a wave breaks, however, linear wave theory no longer applies; in its place cnoidal or solitary wave models (among others) may be suitable. Nevertheless, actual water-wave behavior after the breaking point is complex and difficult to describe mathematically because of nonlinearities, three-dimensional characteristics, and apparent random behavior (Allender et al. 1981; U.S. Army Corps of Engineers 1984).

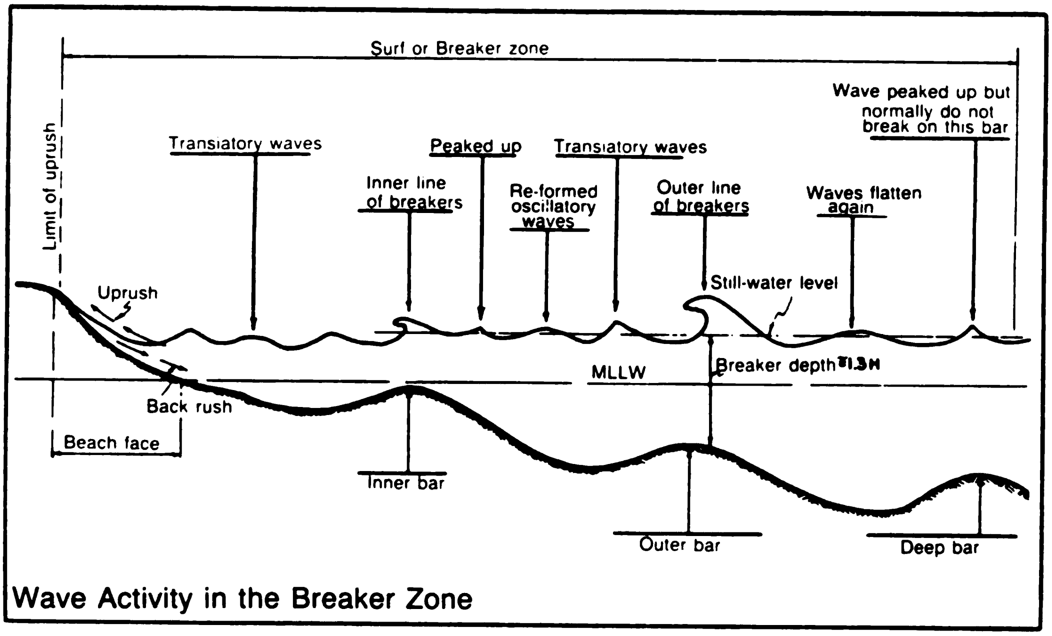


Figure 10. Schematic diagram of waves in the breaker zone. From the *Shore Protection Manual.*

Littoral Transport

Littoral transport is the movement of sediment by waves and currents in the nearshore zone. The process can be subdivided into two categories: 1. movement perpendicular to the shoreline (onshore-offshore transport [Figure 11]) and 2. movement parallel to the shoreline (longshore transport). Sediments carried in the nearshore zone are called littoral drift (U.S. Army Corps of Engineers 1984).

Wave steepness (the ratio of wave height to wave width), sediment size, and beach slope regulate onshore-offshore transport. High, steep waves generally transport material offshore, while low, long-period waves move sediments on shore. It is this process that may remove beaches during storms and rebuild them during a normal wave climate. Waves observed along the Lake Michigan shore, during autumn of 1966 and 1967, had greater heights in the north and longer wave periods toward the south (Liu and Housley 1970). This may be due to the fact that long-period waves are dispersive in the wave spectrum. For example, if a cyclonic storm passes over northern Lake Michigan, only the longer-period waves will reach the southern shores (Dag Nummendal 1986, personal communication).

Longshore transport is caused by waves impinging obliquely on the shoreline. As the waves break in the nearshore zone, sediment is entrained by the turbulence, then transported by the alongshore wave energy component and the current generated by successive breaking waves. The direction of longshore transport

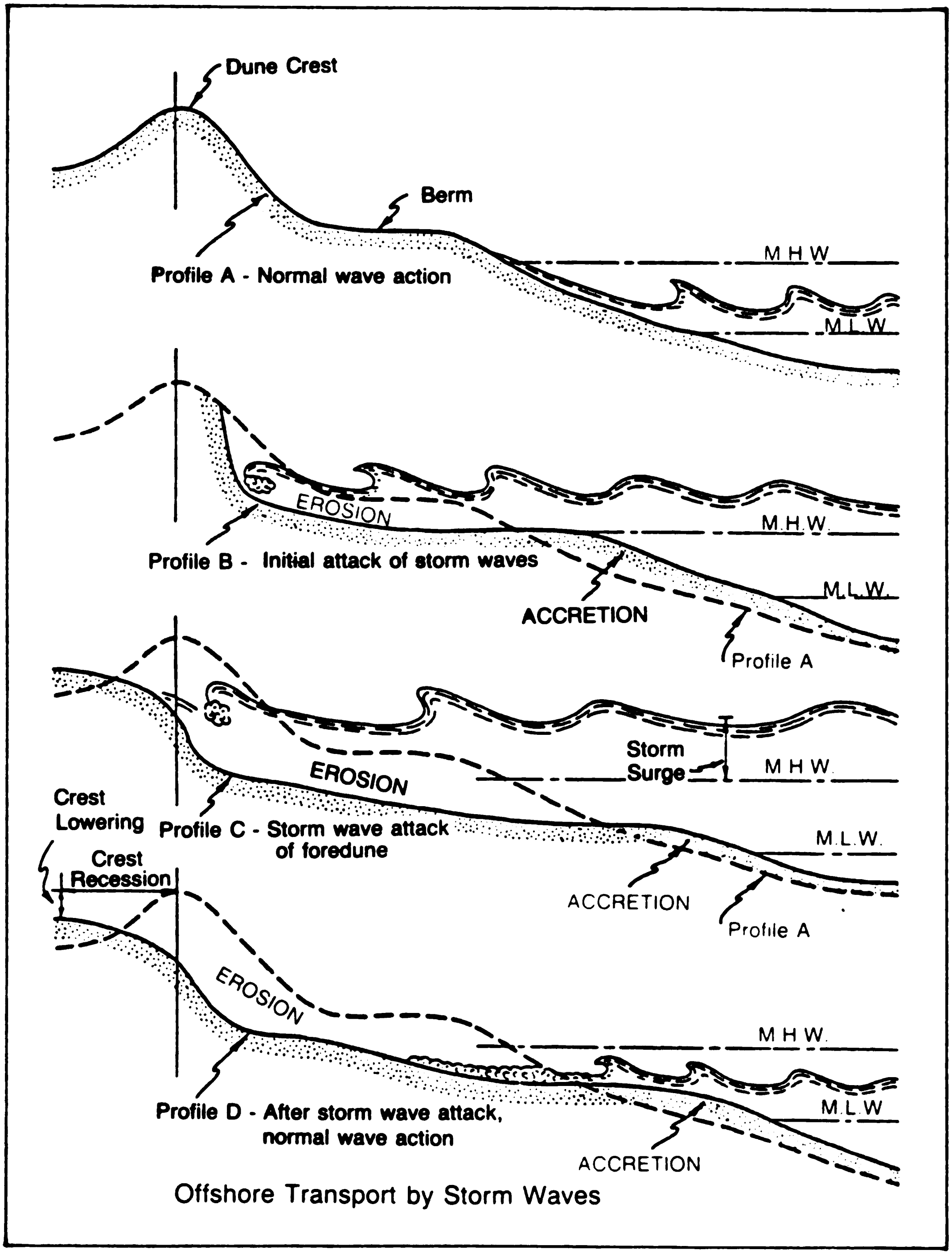


Figure 11. Schematic diagram of offshore transport by storm wave attack on beach and dune. From *Shore Protection Manual.*

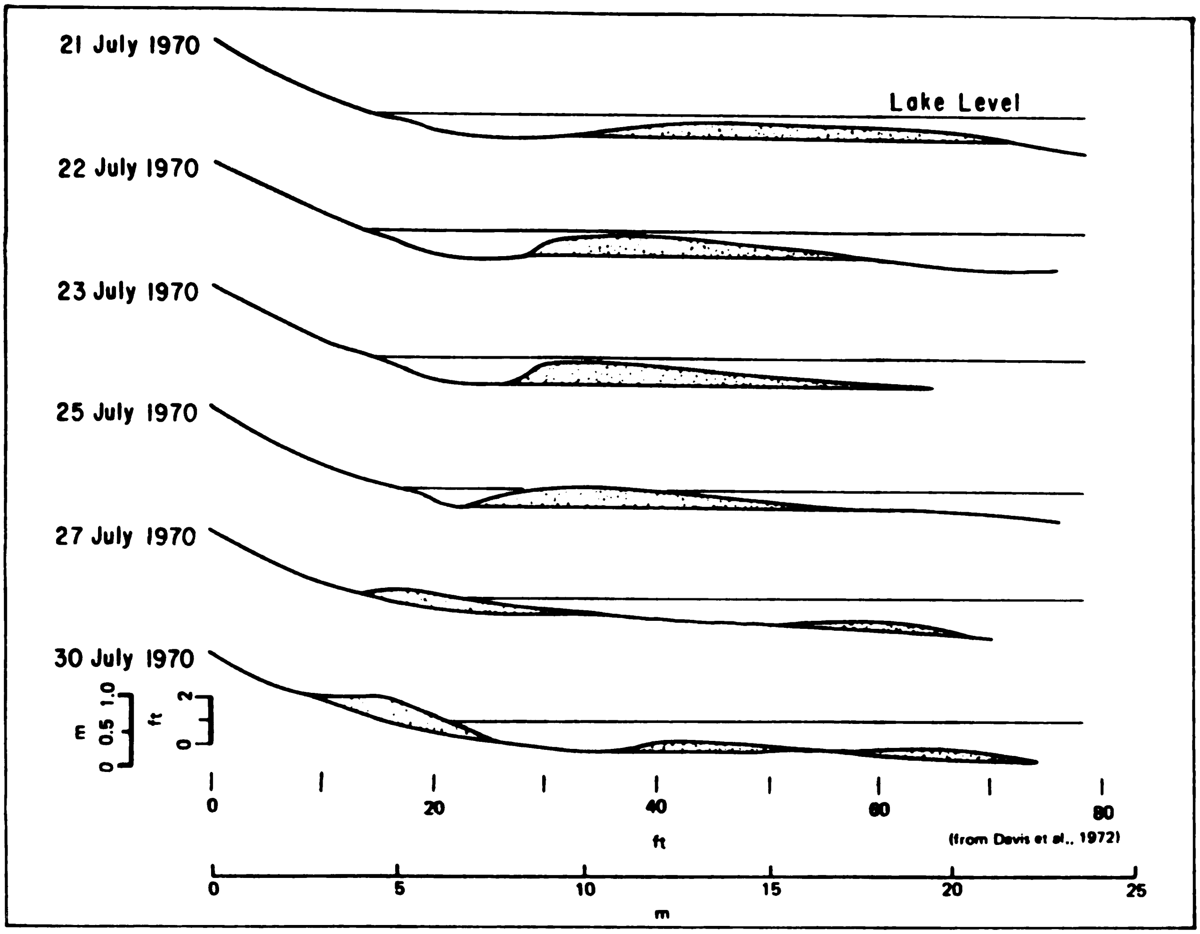


Figure 12. Rapid accretion of ridge-and-runnel at Lake Michigan (Holland, Michigan). From *Shore Protection Manual.*

is a function of the angle of wave incidence to the shoreline. The direction of littoral transport changes as oblique waves approaching the shore change angle and direction. Consequently longshore transport may vary hourly and seasonally. If sediment is consistently removed from a point along the shore, and never replenished, that particular location will experience erosion. Accretion occurs at places where more sediment is supplied than is removed. Some contend that long-term convergence may account for the development of Big and Little Sable Points (Hands 1980). However, the long-term direction of longshore transport on Lake Michigan is not clear; not all sources agree (Figure 13). Recent studies by the Corps of Engineers (1986a, 1986d) assert that at some places net transport may be to the south for some years, then reverse northward. For example, at Grand Haven, Michigan,

> From 1975 to 1984, seven years showed northward movement and three years showed southward movement. Within most years, the movement tended to be northward from spring to summer, and southward from fall to winter.

(U.S. Army Corps of Engineers 1986d). Rates of sediment supply at different sites depend on local shore conditions and shore alinement, as well as the energy and direction of wave approach.

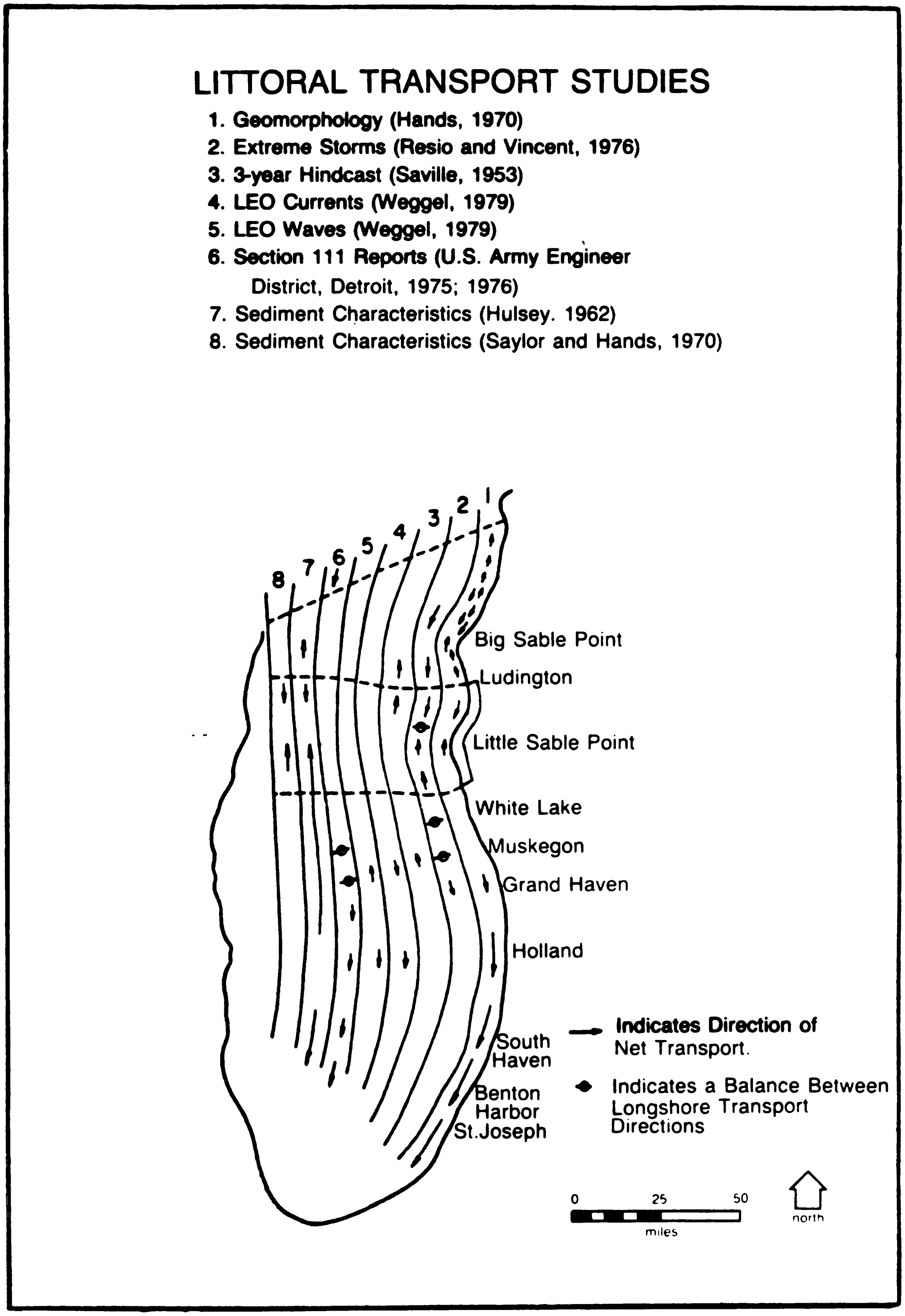


Figure 13. Direction of net longshore transport along the eastern shore of Lake Michigan. Not all sources are in agreement. From Hands 1980.

Storms

The most erosive force acting on Lake Michigan's shore comes from high energy waves generated by storm systems (Brater and Seibel 1973). Many researchers note the connection between intense cyclonic disturbances and severe erosion on Lake Michigan (Birkemeier 1981; Brater n.d.; Brater and Seibel 1973; Buckler 1981; Buckler and Winters 1983; Davis 1976; Gilbert 1986; Hands 1980; Powers 1958; among others). The harshest storms occur from fall to spring. Between November and April two dominant cyclonic tracks converge on the Great Lakes: one from western Canada and the other from the southwestern United States. The consequence of these merging tracks is recurrent cyclonic passage that maintains an elevated wave climate and frequent surges in wave energy that may result in dramatic erosion.

Storms exact their toll regardless of lake level. Naturally, when levels are high, the potential for erosion is greater. Nevertheless, the vertical rise in still-water level on the leeward side of the lake, caused by surface wind stress (wind setup), is sufficient to transmit wave energy into backshore regions and cause significant erosion. Fortunately when water levels are at an annual high in July or August, the wave climate is generally moderate compared with conditions between fall and spring.

Storms are historically linked to erosion. Brater (n.d., p. 3) includes a 1940 storm account by Norman Billings, hydrogeologist for the Department of Conservation:

> Foredune ridges were completely eroded and the waves actually attacked the land mass behind them. Great pine trees, whose locations attested the previous stability of their foundation, were undermined and felled into the lake.... cottage yards disappeared, leaving dwellings which had formerly occupied modest terraces now standing precariously only a few feet from nearly vertical banks.

The severe erosion described in Billings's account occurred during a period of below normal lake levels. Brater (n.d.) emphasized that rapid shore erosion is associated with wave action during large storms that attack and erode the toes of bluffs. Although increased recession rates are a response to high lake levels, the amount is dependent on storm events (Hands 1980). Birkemeier (1981) recorded an average 5.2 feet of recession at 11 out of 17 study sites (on Lake Michigan) following a March storm in 1973. He further observed that high recession occurred during late fall and early spring but was low or nonexistent during summer and periods of ice cover. Brater and Seibel (1973) contended that about 90% of all movement of littoral material during a three year period may be caused by the two or three largest storms, although others disagree. These large, infrequent storms introduce much more energy to the coastal system than the largest monthly waves (that are not associated with storms) because wave energy (in foot-pounds per foot of wave crest per wave length) increases as the square of wave height (King 1959). Therefore as wave height increases, energy increases rapidly.

Ice

Ice normally begins to form on the Lake Michigan shorezone in December and generally persists until March (Figure 14). But during severe winters the ice may cover up to 90% of the lake and endure until the end of April. In contrast, more mild winters are characterized by less than 15% coverage which melts by March (Assel et al. 1983).

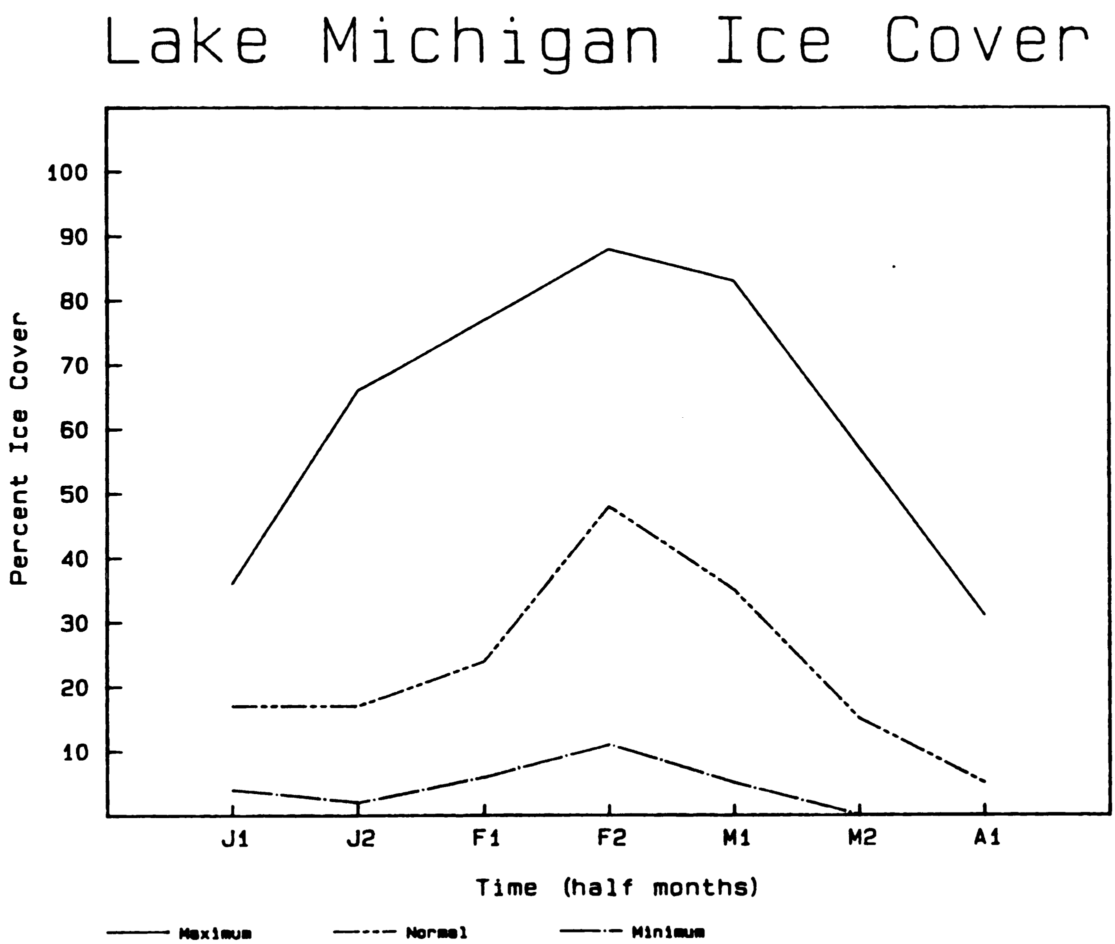


Figure 14. Percentage of ice cover on Lake Michigan.

Ice first forms in northern, shallow areas followed by other shallow and restricted portions along the perimeter of the lake. The most rapid increase in ice extent occurs the last half of February. Ice formation tends to cease in the southern two-thirds of Lake Michigan by March as below-freezing temperatures recede northward. The greatest decrease in ice cover occurs from 1-15 March as ice dissipates shoreward and northward from mid-lake areas (Assel et al. 1983).

Ice accumulates to form a series of ridges parallel to the strand line. Some sand is incorporated into the ice ridges during their formation by wave turbulence. As the ridges grow, they may be held fast by strong, onshore winds and their great mass until, in places, they actually rest on the lake bottom (Davis 1976).

No significant erosion is caused by the extensive ice complex. Instead the ice forms a protective armor that guards the shore against fierce wave attack. January, February, and March have the most frequent storms of any three-month period (Buckler 1981; Buckler and Winters 1983; Davis 1976), but the effects of these storms are virtually negated by the presence of ice, which commonly extends one quarter to 1/2 mile from shore. Thus the Lake Michigan shoreline is essentially static during the most dynamic wave climates where winter ice structures are fully developed.

Summary

Wave activity during high-intensity storms is the fundamental cause of Lake Michigan shore erosion and bluff recession. Storm waves superimposed on high lake levels are potentially the most damaging. However, during summer months, when Lake Michigan is at an annual high, storms are infrequent and of low intensity. Annual low-water periods between fall and spring are a time of recurrent, extreme storminess. Ice development protects the shoreline against persistent winter storm attack. Consequently, the storms most associated with coastal erosion occur in the fall prior to ice formation and in the spring after the ice breaks up. Long-term high lake levels exacerbate erosion along the coastline; however, violent storms have caused severe erosion even during times of record low lake levels (Brater n.d.).

Less common high energy storms are considered more important than more frequent monthly storms of low to intermediate intensity in bluff recession (Buckler 1981; Birkemeier 1981; Brater and Seibel 1973). Separate areas of shoreline typically experience intermittent recession. Thus, coastal erosion that threatens personal property and communities, as well as railway and road networks, is largely the product of severe fall and spring storms.

Chapter 3

DATA AND ANALYSIS RESULTS

Introduction

In this study bluff recession rates are based on measurements of bluff crest retreat while wave energy values are derived through computation. Subsequent analysis is designed to examine the dependence between bluff recession and wave energies associated with fall and/or spring storms (Figure 15). To this end, individual recession rates for 23 sites are compared to wave energies projected for storms with return periods of 5, 10, 20, 50, and 100 years. Pearson's product-moment correlation coefficient is used to measure the extent of association while regression testing indicates how the variables are associated.

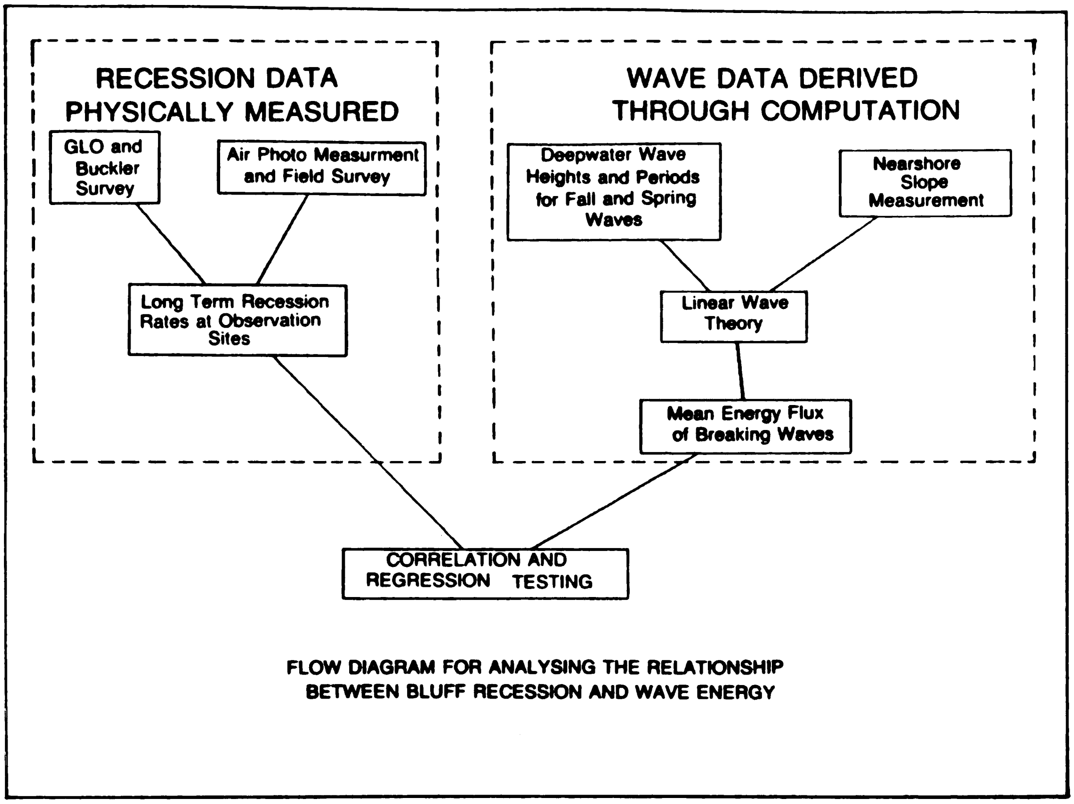


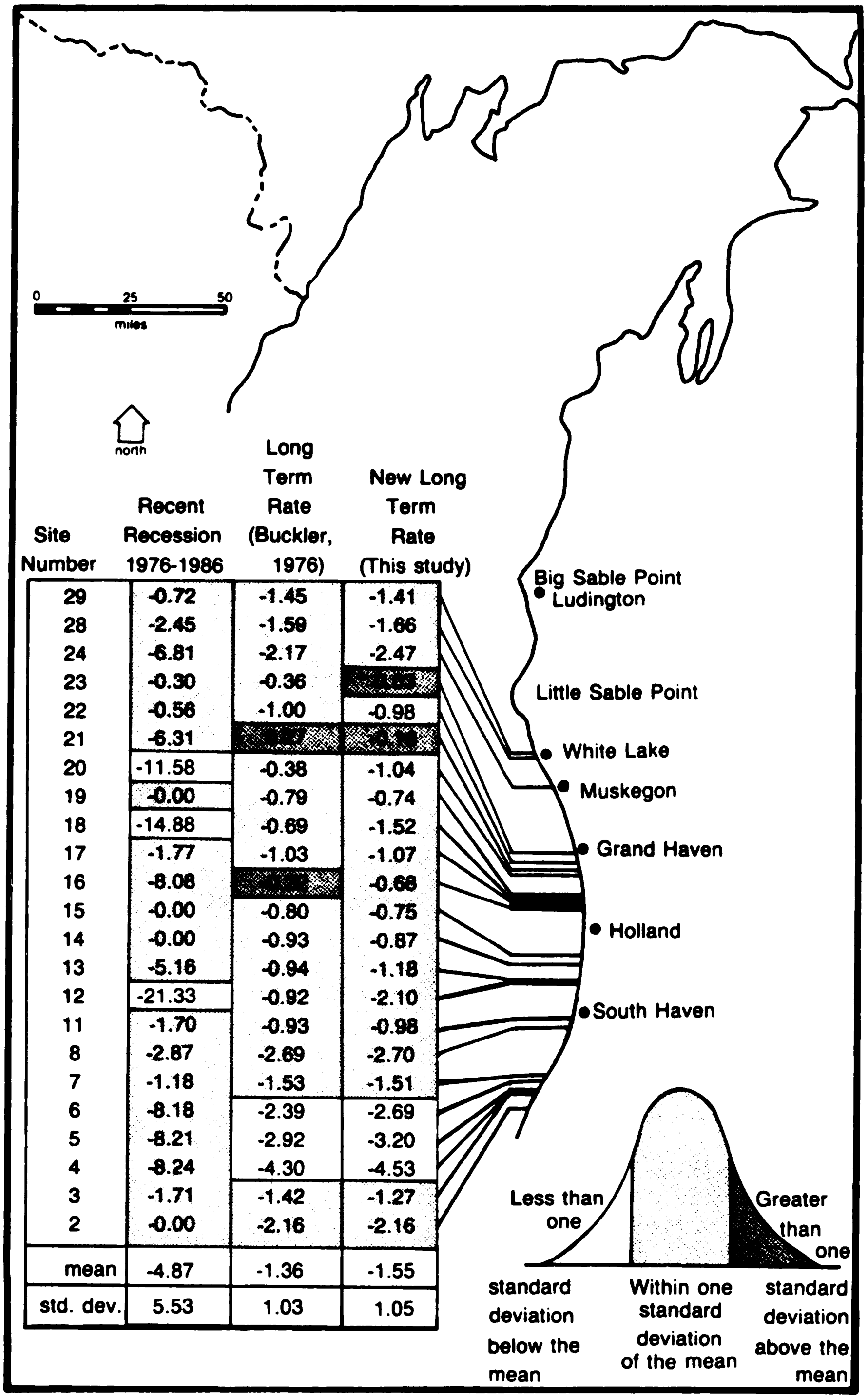
Figure 15. A flow diagram for analyzing the relationship between bluff recession and nearshore wave energy.

Recession Rates

Both short and long-term recession rates are known for 23 sites. The ten-year period between observations made by Buckler in 1976 and measurements completed during this investigation, in 1986, constitute the short-term increment. Long-term intervals generally cover 150 years, the time elapsed since the initial General Land Office survey. The sites and their recession rates are shown in Figure 16. Values exceeding one standard deviation above and below the mean are highlighted to lend scale to the degree of variation among values.

Erosion rates over the past ten years, for all sites, show greater variation than for long-term observations. In the short term, four sites registered no bluff recession while the bluff crest at site number 12 retreated 192.48 feet, more than any of the others, and along with sites 18 and 20 was greater than one standard deviation above the mean. The recession rates do not show any apparent geographic pattern (Figure 16).

Long-term recession rates are relatively consistent with those established by Buckler (1981). Recession rates vary from near zero (sites 21 and 23) to an average of -4.53 feet per year at site 4. The long-term rates are of greater interest because they tend to compensate for fluctuating water levels and may show more clearly the overall influence of storms with varying intensity and frequency, consistent with the return periods incorporated in the wave hindcast model.



Site Number	Recent Recession 1976-1986	Long Term Rate (Buckler, 1976)	New Long Term Rate (This study)
29	-0.72	-1.45	-1.41
28	-2.45	-1.59	-1.66
24	-6.81	-2.17	-2.47
23	-0.30	-0.36	[illegible]
22	-0.56	-1.00	-0.98
21	-6.31	[illegible]	[illegible]
20	-11.58	-0.38	-1.04
19	-0.00	-0.79	-0.74
18	-14.88	-0.69	-1.52
17	-1.77	-1.03	-1.07
16	-8.08	[illegible]	-0.68
15	-0.00	-0.80	-0.75
14	-0.00	-0.93	-0.87
13	-5.16	-0.94	-1.18
12	-21.33	-0.92	-2.10
11	-1.70	-0.93	-0.98
8	-2.87	-2.69	-2.70
7	-1.18	-1.53	-1.51
6	-8.18	-2.39	-2.69
5	-8.21	-2.92	-3.20
4	-8.24	-4.30	-4.53
3	-1.71	-1.42	-1.27
2	-0.00	-2.16	-2.16
mean	-4.87	-1.36	-1.55
std. dev.	5.53	1.03	1.05

Figure 16. Statistical and geographic distribution of bluff recession rates in feet per year.

The long-term recession rates show no gradational spatial trend, either increasing or decreasing along the shore (Figure 16). However, an apparent clustering of higher rates in the south and lower rates in the north seems in agreement with values reported by Buckler (1981) and may support his finding of greater overall recession at the southern end of Lake Michigan.

Seventy-eight percent of the observations fall within one standard deviation of the mean (-1.55 feet per year), which suggests a normal distribution. Furthermore, there is no compelling indication that the values are not normally distributed. Two observations (sites 21 and 23) are less than one standard deviation below the mean, and three observations (sites 4, 5, and 6) are greater than one standard deviation above the mean.

Figures 17 through 19 are representative of the study area and variability in recession rates. Additional data concerning site observations are given in appendix A.

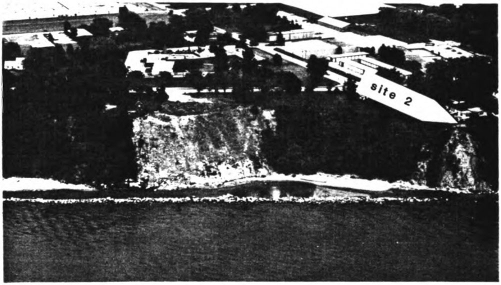


Figure 17. Site number 2 has experienced no recession since emplacement of heavy limestone block revetment and groin system in 1971. Photo date: August 1986.

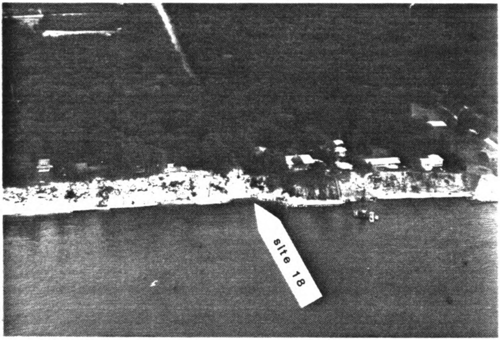


Figure 18. The bluff at site number 18 has receded 176.10 feet in 10 years. Although a recession rate of -14.88'/year is high for the short term, the long-term rate of -1.52'/year is close to the mean (-1.55'/year). Note the close proximity of houses to the bluff crest and the effect of individual structures that front private property at the strand line. The barge in the foreground is equipped with a pile driver and material to construct or repair shore protection structures. Photo date: August 1986.

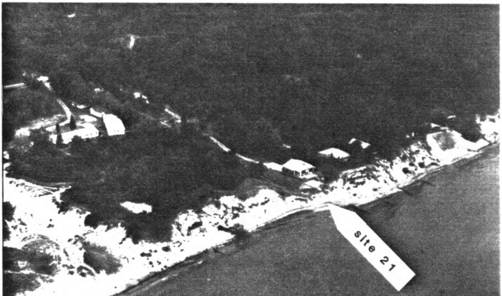


Figure 19. Site number 21 has an extremely low, long-term recession rate of -0.16'/year. Still, after several years, houses are dangerously close to the shoreline. South is to the right in this photo; note that little or no sand is accumulated in the groins along the shore. Littoral drift appears to have been to the north recently. Photo date: August 1986.

Wave Energy

Wave energy data for this study are calculated using linear wave theory, values from the Resio and Vincent hindcast model, and a normalized nearshore slope at each site. Deep water wave heights and periods are interpolated for observation sites between hindcast points (Figure 20). Heights and periods for spring and fall waves of 5, 10, 20, 50, and 100 year return periods (Appendix A) combine with the nearshore slope at each site to yield wave energy values given as *mean energy flux* in Table 1. The *mean energy flux*, which is in units of foot-pounds/foot-second, can be thought of as the amount of energy that is transmitted horizontally landward by a wave when it first breaks. Table 1 presents the wave energy associated with storm events of varying frequency and the long-term, average annual recession rate at each observation site.

Since wave energy is a function of both storm intensity and lake geometry, these values (unlike bluff recession) exhibit a gradational trend along the shore. In general, highest spring energy values are found in the northern part of the study area for frequent return periods (5 years) and toward the central part for the more infrequent events (100 years). Fall wave energies tend to be greater along the central and northern portion of shore for 5-year storms but lower along the central reach for 100-year storms. Resio and Vincent (1976, p. 47) suggest that the disparity between time limitation and fetch limitation may explain the distribution of wave values at this end of the lake. Fall storms generally show intensities about four times greater than spring storms of the same return period. This could result from instability between the warm, autumn lake surface and cooler air aloft, which may create a greater tendency for coupling between surface and upper atmospheric winds.

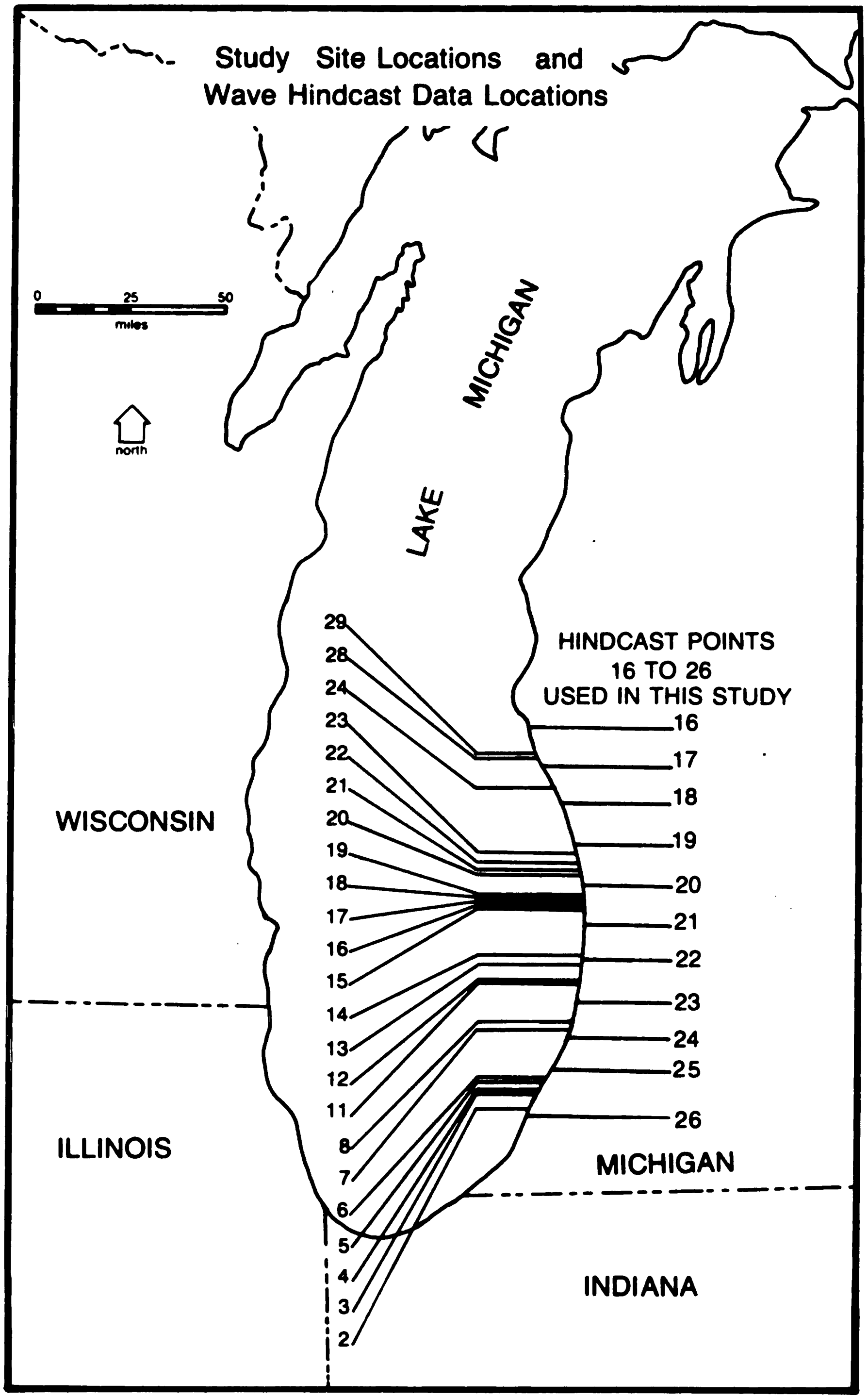


Figure 20. Locations of hindcast points and observation sites.

Table 1. WAVE ENERGIES.

WAVE ENERGIES

SITE NUMBER	RECESSION RATE	SPRING 5 YEAR WAVE	SPRING 10 YEAR WAVE	SPRING 20 YEAR WAVE	SPRING 50 YEAR WAVE	SPRING 100 YEAR WAVE	FALL 5 YEAR WAVE	FALL 10 YEAR WAVE	FALL 20 YEAR WAVE	FALL 50 YEAR WAVE	FALL 100 YEAR WAVE
2	-2.16	11,741	14,944	22,549	32,539	42,865	40,202	46,223	51,510	66,081	82,952
3	-1.27	11,476	15,447	21,519	31,995	40,847	39,765	45,732	52,224	68,277	87,173
4	-4.53	11,066	15,447	21,519	31,995	40,847	39,765	45,732	52,224	69,018	88,030
5	-3.2	11,066	15,447	21,519	31,632	40,847	39,328	45,240	52,224	69,762	88,891
6	-2.69	10,810	15,447	20,888	31,632	39,861	39,328	45,240	52,299	69,762	89,756
7	-1.51	11,852	14,753	24,131	40,747	53,968	44,001	49,126	57,168	74,961	96,811
8	-2.70	11,852	14,753	24,942	42,865	59,110	44,001	49,126	57,168	78,086	100,497
11	-0.98	12,326	15,567	24,846	44,665	67,541	42,581	48,764	57,379	79,002	99,577
12	-2.10	12,868	16,183	24,846	41,021	57,430	42,108	48,827	58,088	79,002	94,983
13	-1.18	13,238	17,219	23,844	35,721	48,961	40,689	48,376	58,152	75,864	88,765
14	-0.87	13,795	17,540	22,864	32,583	44,502	39,742	47,848	58,173	72,003	84,459
15	-0.80	14,944	21,143	31,165	45,732	58,587	45,240	46,734	62,642	79,745	88,891
16	-0.68	14,944	23,056	31,165	45,732	58,587	45,240	46,734	62,642	79,745	88,891
17	-1.07	14,944	23,056	31,165	45,732	58,587	45,732	50,141	66,081	82,990	95,923
18	-1.80	14,944	22,666	31,054	45,151	57,319	45,732	50,710	66,081	84,628	96,834
19	-0.74	14,944	22,666	31,054	45,151	57,319	45,732	51,280	67,477	85,472	98,655
20	-1.04	15,251	22,281	30,589	44,474	55,348	46,814	56,658	72,625	92,321	109,128
21	-0.16	15,760	22,281	30,127	42,303	52,856	47,408	57,916	73,400	93,215	110,118
22	-0.98	16,604	22,281	28,882	39,229	49,824	49,738	59,263	74,179	95,016	113,114
23	+0.03	17,815	22,281	27,672	35,299	44,574	52,774	63,281	75,796	96,834	117,172
24	-2.47	17,596	21,898	27,350	34,409	46,814	51,510	64,637	82,068	107,162	126,697
28	-1.66	17,596	21,634	29,100	38,367	53,559	47,574	60,000	75,106	99,476	112,050
29	-1.41	19,355	21,634	29,100	38,367	52,927	48,092	60,625	75,106	99,476	112,050

Wave energy values are given at breaking conditions of deep water waves as "mean energy flux" in units of foot-pounds/foot-second.

Analysis

Correlation and regression tests are used to analyze the relationship between long-term average annual bluff recession and wave energy estimates. The amount of association or interdependence is assessed with Pearson's product-moment correlation coefficient in a pair-wise test. Pearson's coefficients are actually calculated, using the recession rate at each site paired with the corresponding wave energy value for each return period. Results are presented in Table 2.

Table 2. PEARSON PRODUCT-MOMENT CORRELATION COEFFICIENTS ANALYZING LONG-TERM ANNUAL RECESSION RATES WITH STORM WAVE ENERGIES FOR VARIOUS RETURN PERIODS.

SPRING WAVES					FALL WAVES				
5YR	10YR	20YR	50YR	100YR	5YR	10YR	20YR	50YR	100YR
0.522	0.579	0.600	0.491	0.415	0.477	0.341	0.464	0.380	0.244

Correlation coefficients are a measure of association or interdependence between sets of variables. Values range from -1 (perfect negative correlation) to +1 (perfect positive correlation). If there is no association, the coefficient is 0.

The results of linear regression techniques used to evaluate how the variables are related are shown in Table 3. Wave energy is the independent variable, used to predict the dependent variable -- bluff recession rate, in seeking a linear functional relationship. A second analysis using the natural logarithm of wave energy values to linearize a power law relationship gives slightly better results. The logarithmic transformation implies a nonlinear relationship between bluff recession and wave energy. This means a change in the form of the regression equation from:

$$y = mx + b$$

to:

$$y = m\,(\ln x) + b$$

where:

y = predicted value of bluff recession rate

x = wave energy value

m and b = regression coefficients.

Table 3. LINEAR REGRESSION RESULTS; PREDICTING LONG-TERM ANNUAL RECESSION RATE WITH MEAN ENERGY FLUX FOR VARIOUS RETURN PERIODS.

	SPRING WAVES					FALL WAVES				
	5YR	10YR	20YR	50YR	100YR	5YR	10YR	20YR	50YR	100YR
Adjusted R^2	0.238	0.304	0.330	0.205	0.133	0.191	0.074	0.178	0.104	0.015
Significance Level	0.011	0.004	0.002	0.017	0.049	0.021	0.111	0.026	0.074	0.261
	ln SPRING WAVES					*ln* FALL WAVES				
Adjusted R^2	0.283	0.308	0.340	0.214	0.152	0.200	0.087	0.209	0.129	0.021
Significance Level	0.005	0.004	0.002	0.015	0.038	0.019	0.093	0.016	0.052	0.240

In general R^2 is the proportion of variance in the dependent variable explained by the independent variable and regression equation. Significance reflects area outside a confidence interval, assuming a known distribution. For example if significance=0.05; this means 5% (of the distribution) is outside the confidence interval, or there is a 95% confidence that R^2 is correct.

Summary

Bluff recession rates within the area studied seem to constitute a normal distribution but show no geographic patterns in their ordering along the shore. In contrast, estimates of wave energy exhibit a gradational trend between high and low values along the coast. Bluff recession rates, the dependent variable of interest, are compared with wave energies (the independent variable) to examine this relationship.

Statistical tests show a moderate relationship between recession rates and wave energies associated with storms of certain return periods. Spring waves of 20, 10, and 5 year return periods have the highest correlation coefficients. Regression testing suggests a nonlinear relationship, using the natural logarithm of wave energy to predict bluff recession yields the highest R^2 values. The strongest relationships from this study are spring 20, 10, and 5 year waves, which account for 34%, 31%, and 28% of the variance in bluff recession rates, respectively.

Chapter 4

DISCUSSION AND CONCLUSIONS

Introduction

The two objectives of this study are 1. to obtain long and short-term bluff recession data at previously studied sites and 2. to examine the hypothesis that the variability in recession rates are related to storm intensity and nearshore wave energy. Significant results are addressed in the following discussion. Additional findings, pertinent to both the technical design of the investigation and coastal morphology, are also considered.

Discussion

Short and long-term recession data for 23 sites, previously investigated by Powers (1958) and more recently by Buckler (1973a, 1981), provide a basis for several findings. Variation in recession rates among sites is greater over short periods (1976-1986) than long periods (middle 1800's to 1986). The standard deviations for short and long-period observations are 5.53 and 1.05 (feet/year), respectively. This suggests that, although the crest line as a whole is receding, erosion occurs sporadically at individual locations. Certain sites may loose several feet during a few years and then remain somewhat more stable while other locations begin to recede.

Even though the long-term recession rates are five times less variable than short-term rates, and subsequently more closely distributed about their mean, they nevertheless express a degree of variation. Since the values are in fact rates, the longer the observation period, the greater the difference in actual recession. For example, neither site 11 (rate = -0.98 feet/year) or site 8 (rate = -2.70 feet/year) shows statistically significant variation from the mean (rate = -1.55 feet/year). However, over a 100-year period, site 8 would lose 270 feet of bluff compared to only 98 feet at site 11. Exactly how great the difference is may be a matter of scale and perspective. A property owner at site 8 would certainly regard losing 270 feet a substantially greater loss than 98 feet. Yet in a geomorphic context of hundreds of miles of coastline shaped over thousands of years, the difference may be less consequential.

The second objective is to examine the hypothesis that bluff recession is related to wave energy. Acceptable significance levels for correlation and regression coefficients were not set in advance because there are no similar investigations to provide a comparative measure or indicate appropriate values. Therefore, this research *examines* rather than *tests* these relationships.

The analysis indicates a nonlinear relationship. Spring storm waves with return periods of 20, 10, and 5 years can each account for approximately 30% of the variance in bluff recession rates, but waves associated with spring 50 and 100 year storms explain a much lower proportion of the variance (13-20%). Although fall waves are not as strongly related to recession as spring waves, the R^2 values indicate a similar pattern (5 and 20-year return intervals accounting for more variance than 50 and 100-year phenomena).

Less than half of the variation in bluff recession rates is explained by the regression equation. Thus, using this model to predict bluff recession as a function of wave energy is not practical; predictions based on established, long-term recession rates would yield better results. On the other hand, the R^2 values are high enough to suggest that there is a relationship between bluff recession and wave energy. With appropriate refinements in this model, the association may emerge more clearly. Therefore, the regression results are considered moderately successful and encouraging. Assuming that there *is* a relationship between wave energy and bluff recession, there are at least two possibilities that might explain the stronger association with frequent storms of moderate intensity rather than infrequent, high energy (50 and 100-year) events.*

First, nearshore wave energies, for this study, are calculated from deep water wave values projected by Resio and Vincent (1976). Their hindcast model is based on 62 years of wind data. Naturally the margin of error about infrequent 50 and 100-year wave projections, based on only 62 years of data, is greater than the error about 5, 10, and 20 year wave predictions. It is therefore possible that the values for 50 and 100-year waves are not representative of actual conditions. If this is the case, any error in the Resio and Vincent model would be incorporated into this study and affect the regression tests and subsequent results.

The second possibility is that the Resio and Vincent 50 and 100-year wave values do approximate actual conditions. In this case, the lower association between high wave energy and bluff recession may imply that storm waves of moderate intensity and frequency (of occurrence) are morphologically more influential in shaping the coast line than infrequent, high energy waves. This notion is consistent with postulations by Wolman and Miller (1960) in their article, *Magnitude and frequency of forces in geomorphic processes*.

* The 5, 10, 20, 50, and 100-year storm events are probabilities. For instance, a 100-year storm has a 1% likelihood of occurrence any given year.

As applied to bluff recession, the rate at which a coast-line, composed of unconsolidated material, is shaped by wave energy at various locations along the shore depends on the distribution of wave energy in time as well as in magnitude. The enormous wave energies associated with rare or infrequent storms are not implicitly the most significant forces shaping the coast. As Wolman and Miller (1960, p. 5) indicate,

> The relative amount of "work" done during different events is not necessarily synonymous with the relative importance of these events in forming a landscape or a particular feature of a landscape. The effectiveness of an event of a given frequency in terms of its performance of work is measurable both by its magnitude and by the frequency with which it recurs.

Work, in this sense, is the product of frequency times magnitude. In the specific instance of bluff recession on Lake Michigan,

$$\text{work} = \text{return period} * \text{mean energy flux.}$$

A literal interpretation of wave return periods may help illustrate this concept. During the course of a century, the coast may experience 100-year storm waves only once; and in the process of the same 100 years potentially be exposed to five 20 year storms, ten 10-year storms, and twenty 5-year storms. Erosion during these relatively moderate but more frequent events may exceed the changes made by the rare, high energy storms and thus become the dominant geomorphic force.

As an example, Figure 21 shows the relative amounts of potential work accomplished over a 100-year period at site 18 for spring waves of different return periods. This

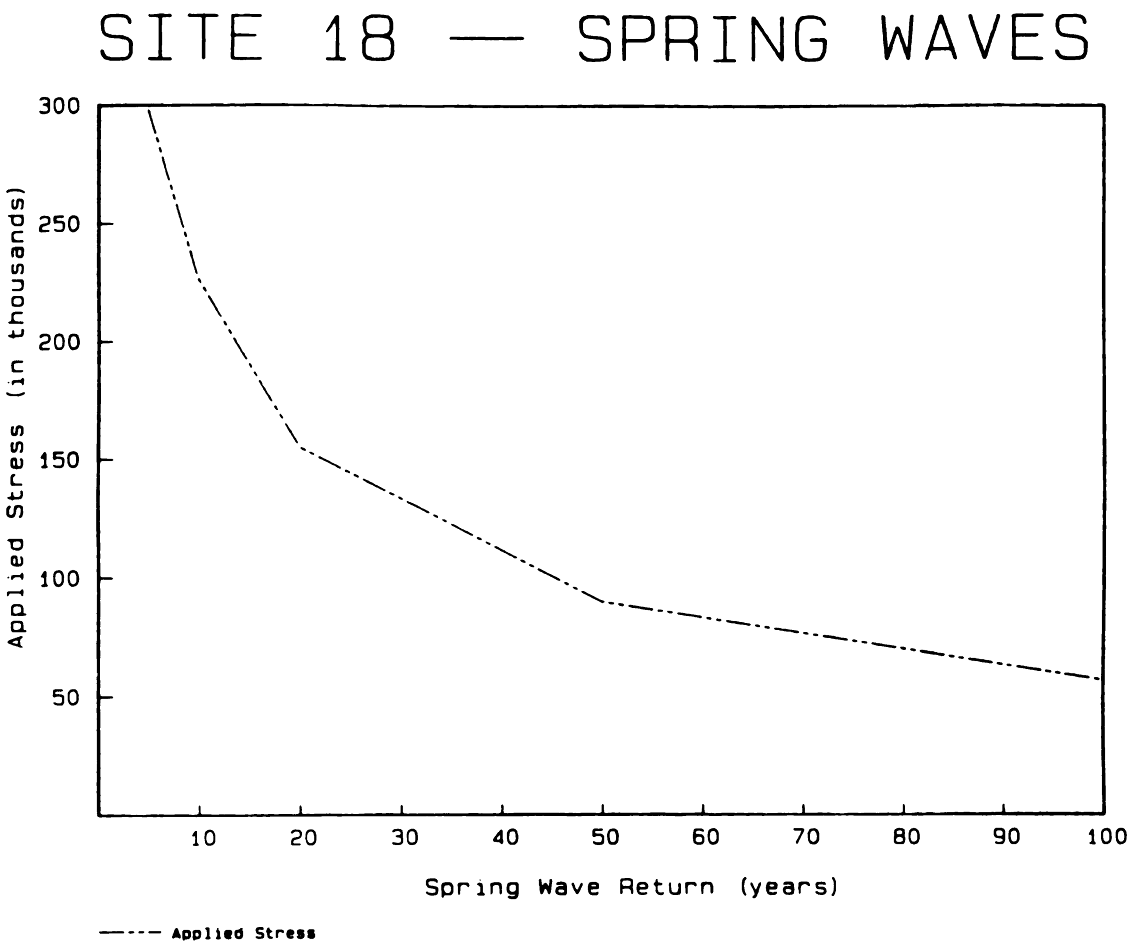


Figure 21. Work accomplished by spring waves at site number 18.

generalization can only hold true providing that the wave magnitude during recurrent events exceeds some threshold value to move sediments and induce bluff erosion. For instance, if 5-year storms do not generate enough energy to produce significant offshore and longshore transport, the concept of geomorphic work cannot be applied. Consequently the effect of 5-year storms would be negligible compared with storms that do exceed the threshold energy requirement.

An important distinction between Wolman and Miller's research (1960) and this study is that they cited examples of geomorphic events that were both constructional and destructional. Although waves may impart erosional and depositional change in the beach profile, only destructional processes occur on the bluffs examined. Wolman and Miller (1960, p. 72) note, "There is a notable lack of examples demonstrating effectiveness of moderate events of frequent occurrence in molding erosional landforms." This study may be one such example.

Finally, the low correlation between potential wave energy and bluff crest recession rates reinforces the findings of other similar studies that concentrated on shorezone geomorphology. In combination, other investigations indicate that erosion is a complex process involving several variables. The influence of other factors such as soil cohesion, lithology, lake level fluctuations, runoff, and destablization due to ground water should not be discounted. Thus, a simple bivariate relationship is not likely to relate or explain the intricacies of a dynamic system with numerous other forces impinging on it. Yet the development of techniques to study and quantify these simple relationships contribute significantly, by describing fundamental interactions necessary to construct more comprehensive and dimensionally correct models.

Suggestions for Future Research

This study provides a first iteration model to investigate the association between wave energy and Lake Michigan coastal erosion. The model is restricted to a small sample area and based on probabilities for wave energy. During the course of this study certain improvements became apparent which deserve further investigation.

Several assumptions are incorporated into the study as a result of using the hindcasting concept. Wave return periods are based on the statistical probability of storms, with certain magnitudes, recurring in a 100-year interval. Since these storms do not actually recur according to this schedule, error is introduced into this design. A model that includes actual meteorological data may produce more accurate results. By researching historic synoptic wind charts, storms with magnitudes that correspond to the hindcast storm intensities could be identified. Approximations of deep water wave parameters, calculated with procedures described by Resio and Vincent (1976), could be improved by using actual storm track and wind speed information. Better estimations of nearshore wave magnitude and incidence, including longshore energy flux, could be determined using true storm track data. Actual storm dates could then be referenced to an exact lake elevation, on those dates, to estimate beach width and wave proximity to the toe of the bluff slopes. Improved accuracy of nearshore, wave energy estimates would greatly enhance this model and may help to clarify the connection between waves and erosion.

Conclusion

The Lake Michigan shoreline forms a dynamic interface between land and water where numerous physical forces continually interact. Bluff erosion is a destructional coastal process which is caused, in part, by wave energy. This study is one of the first to examine quantitatively the relationship of wave energy and bluff recession at numerous sites. Significant findings of this investigation can be summarized in three main points. First, the results show only moderate success in linking bluff recession to wave energy, but future improvements in design may reveal more about the association. Second, the data suggest that relatively frequent storms (5 to 20-year return periods) of moderate intensity are morphologically more significant than rarer events of greater magnitude. This notion is consistent with a similar concept by Wolman and Miller (1960) that, over a period of time, landscapes are a function of "work," which is the product of the frequency of an event times its magnitude. Finally, the low correlation level is a reminder that coastal processes are complex. Bluff recession results from the interaction of numerous physical factors and cannot be fully explained by simply investigating one of them. However, this study provides a basis to understand further the relationship between wave energy and bluff recession and may contribute, in the future, to more comprehensive investigations.

GLOSSARY OF TERMS

GLOSSARY OF TERMS*

ACCRETION. May be either natural or artificial. Natural accretion is the buildup of land, solely by the action of the forces of nature, on a beach by deposition of water- or airborne material. Artificial accretion is a similar buildup of land by reason of an act of man, such as the accretion formed by a groin, breakwater, or beach fill deposited by mechanical means.

ALLUVIUM. Soil (sand, mud, or similar detrital material) deposited by streams, or the deposits formed.

ALONGSHORE. Parallel to and near the shoreline; LONGSHORE.

ARMOR UNIT. A relatively large quarrystone or concrete shape that is selected to fit specified geometric characteristics and density. It is usually of nearly uniform size and usually large enough to require individual placement. In normal cases it is used as primary wave protection and is placed in thicknesses of at least two units.

ARTIFICIAL NOURISHMENT. The process of replenishing a beach with material (usually sand) obtained form another location.

ATTENUATION. (1) A lessening of the amplitude of a wave with distance from the origin. (2) The decrease of water-particle motion with increasing depth. Particle motion resulting from surface oscillatory waves attenuates rapidly with depth, and practically disappears at a depth equal to a surface wavelength.

BACKSHORE. That zone of the shore or beach lying between the foreshore and the coastline comprising the berm or berms and acted upon by waves only during severe storms, especially when combined with exceptionally high water.

BANK. A landward-facing steep bluff or sharp slope of unconsolidated material landward of the shoreline; the bluff.

BAR. A submerged or emerged embankment of sand, gravel, or other unconsolidated material built on the lake floor in shallow water by waves and currents.

BATHYMETRY. The measurement of depths of water in oceans, seas, and lakes; also information derived from such measurements.

* All definitions from the *Shore Protection Manual* (1984) and Buckler (1981).

BEACH. The zone of unconsolidated material that extends landward from the low water line to the place where there is marked change in material or physiographic form, or to the line of permanent vegetation (usually the effective limit of storm waves). The lakeward limit of a beach-- unless otherwise specified-- is the mean low water line. A beach includes FORESHORE and BACKSHORE. See also SHORE.

BEACH EROSION. The carrying away of beach materials by wave action, tidal currents, littoral currents, or wind.

BEACH WIDTH. The horizontal dimension of the beach measured normal to the shoreline.

BLUFF. A lakeward-facing steep bank or sharp slope of unconsolidated material landward of the shoreline; the bank.

BLUFF BASE. The point or line of abrupt change in slope at the bottom of the bluff; the bluff toe.

BLUFF CREST. The point of line of abrupt change in slope at the top of the bluff; the bluff line.

BLUFF FACE. The lakeward facing inclined surface of the bluff; the bluff slope.

BLUFF LINE. The point or line of abrupt change in slope at the top of the bluff; the bluff crest.

BLUFF TOE. The point or line of abrupt change in slope at the bottom of the bluff; the bluff base.

BOTTOM. The ground or bed under any body of water; the bottom of the lake.

BOTTOM (nature of). The composition or character of the bed of a lake or other body of water (e.g., clay, coral, gravel, mud, ooze, pebbles, rock, shell, shingle, hard, or soft).

BOULDER A rounded rock more than 10 inches in diameter; larger than a cobblestone.

BREAKER. A wave breaking on a shore, over a reef, etc. Breakers may be classified in four types:

SPILLING-- bubbles and turbulent water spill down front face of wave. The upper 25% of the front face may become vertical before breaking. Breaking generally occurs over quite a distance.

PLUNGING-- crest curls over air pocket; breaking is usually with a crash. Smooth splash-up usually follows.

COLLAPSING-- breaking occurs over lower half of wave, with minimal air pocket and usually no splash-up. Bubbles and foam present.

SURGING-- wave peaks up, but bottom rushes forward from under wave, and wave slides up beach face with little or no bubble production. Water surface remains almost plane except where ripples may be produced on the beach face during runback.

BREAKER DEPTH. The still-water depth at the point where a wave breaks. Also called BREAKING DEPTH.

BREAKER ZONE. The area a water bounded by the beach and the plunge line; the plunge line is the line along which the highest waves break.

CELERITY. Wave speed.

CHANNEL. (1) A natural or artificial waterway of perceptible extent which either periodically or continuously contains moving water, or which forms a connecting link between two bodies of water. (2) The part of a body of water deep enough to be used for navigation through an area otherwise too shallow for navigation.

CHART DATUM. The plane or level to which soundings (or elevation) or tide heights are referenced (usually LOW WATER DATUM).

CLIFF. A high, steep face of rock; a precipice.

CNOIDAL WAVE. A type of wave in shallow water (i.e., where the depth of water is less than 1/8 to 1/10 the wavelength). The surface profile is expressed in terms of the Jacobial elliptic function *cn u*; hence the term cnoidal.

COAST. A strip of land of indefinite width (may be several kilometers) that extends from the shoreline inland to the first major change in terrain features.

COASTAL AREA. The land and lake area bordering the shoreline.

COASTLINE. (1) Technically, the line that forms the boundary between the COAST and SHORE. (2) Commonly, the line that forms the boundary between the land and the water.

CONTOUR. A line on a map or chart representing points of equal elevation with relation to a DATUM. It is called an isobath when connecting points of equal depth below a datum. Also called DEPTH CONTOUR.

CONVERGENCE. (1) In refraction phenomena, the decreasing of the distance between orthogonals in the direction of wave travel. Denotes an area of increasing wave height and energy concentration. (2) In wind-setup phenomena, the increase in setup observed over that which would occur in a equivalent rectangular basin of uniform depth, caused by changes in planform of depth; also the decrease in basin width or depth causing such increase in setup.

CREST OF WAVE. (1) The highest part of a wave. (2) That part of the wave above still-water level.

CURRENT, LITTORAL. Any current in the littoral zone caused primarily by wave action; e.g., LONGSHORE CURRENT, RIP CURRENT.

CURRENT, LONGSHORE. The littoral current in the breaker zone moving essentially parallel to the shore, usually generated by waves breaking at an angle to the shoreline.

CURRENT, NEARSHORE. A current in the NEARSHORE ZONE.

DECAY DISTANCE. The distance waves travel after leaving the generating area (FETCH).

DECAY OF WAVES. The change waves undergo after they leave a generating area (FETCH) and pass through a calm, or region of lighter winds. In the process of decay, the significant wave height decreases and the significant wavelength increases.

DEEP WATER. Water so deep that surface waves are little affected by the lake bottom. Generally, water deeper than one-half the surface wavelength is considered deep water.

DEPTH. The vertical distance form a specified tidal datum to the sea floor.

DEPTH OF BREAKING. The still-water depth at the point where the wave breaks. Also BREAKER DEPTH.

DIFFRACTION (of water waves). The phenomenon by which energy is transmitted laterally along a wave crest. When a part of a train of waves is interrupted by a barrier, such as a breakwater, the effect of diffraction is manifested by propagation of waves into the sheltered region within the barrier's geometric shadow.

DIVERGENCE. (1) In refraction phenomena, the increasing of distance between orthogonals in the direction of wave travel. Denotes an area of decreasing wave height and energy concentration. (2) In wind-setup phenomena, the decrease in setup observed under that which would occur in an equivalent rectangular basin of uniform depth, caused by changes in planform or depth. Also the increase in basin width or depth causing such decrease in setup.

DOWNDRIFT. The direction of predominant movement of littoral materials.

DUNES. Ridges or mounds of loose, windblown material, usually sand.

DURATION. In wave forecasting, the length of time the wind blows in nearly the same direction over the FETCH (generating area).

DURATION MINIMUM. The time necessary for steady-state wave conditions to develop for a given wind velocity over a given fetch length.

EMBANKMENT. An artificial bank such as a mound or dike, generally built to hold back water or to carry a roadway.

EMBAYED. Formed into a bay or bays, as an embayed shore.

EMBAYMENT. An indentation in the shoreline forming an open bay.

ENERGY COEFFICIENT. The ratio of the energy in a wave per unit crest length transmitted forward with the wave at a point in shallow water to the energy in a per crest length transmitted forward with the wave in deep water. On refraction diagrams this is equal to the ratio of the distance between a pair of orthogonals at a selected shallow-water point to the distance between the same pair of orthogonals in deep water. Also the square of the REFRACTION COEFFICIENT.

EOLIAN SANDS. Sediments of sand size or smaller which have been transported by winds. They may be recognized in marine deposits off desert coasts by the greater angularity of the grains compared with waterborne particles.

EROSION. The wearing away of land by the action of natural forces. On a beach, the carrying away of beach material by wave action, littoral currents, or by deflation.

ESCARPMENT. A more or less continuous line of cliffs or steep slopes facing in one general direction which are caused by erosion or faulting.

FEELING BOTTOM. The initial action of a deepwater wave, in response to the bottom, upon running into shoal water.

FETCH. The area in which waves are generated by a wind having a fairly constant direction and speed. Sometimes used synonymously with FETCH LENGTH.

FETCH LENGTH. The horizontal distance (in the direction of the wind) over which a wind generates waves or creates a WIND SETUP.

FOREDUNE. The front dune immediately behind the backshore.

FORESHORE. The part of the shore, lying between the crest of the lakeward berm (or upper limit of wave wash) and the mark that is ordinarily traversed by the uprush and backrush of the waves.

GENERATION OF WAVES. (1) The creation of waves by natural or mechanical means. (2) The creation and growth of waves caused by a wind blowing over a waver surface for a certain period of time. The area involved is called the GENERATING AREA or FETCH.

GEOMETRIC SHADOW. In wave diffraction theory, the area outlined by drawing straight lines paralleling the direction of wave approach through the extremities of a protective structure. It differs from the actual protected area to the extent that the diffraction and refraction effects modify the wave pattern.

GEOMORPHOLOGY. That branch of geography and geology which deals with the form of the Earth, the general configuration of its surface, and the changes that take place in the evolution of landform.

GRADIENT (GRADE). With reference to winds or currents, the rate of increase or decrease in speed, usually in the vertical; or the curve that represents this rate.

GROIN. A shore protection structure built (usually perpendicular to the shoreline) to trap littoral drift or retard erosion of the shore.

GROUND WATER. Subsurface water occupying the zone of saturation. In a strict sense, the term is applied only to water below the water table.

GROUP VELOCITY. The velocity of a wave group. In deep water, it is equal to one-half the velocity of the individual waves within the group.

HINDCASTING, WAVE. The use of historic synoptic wind charts to calculate characteristics of waves that probably occurred at some past time.

JETTY. On open coasts, a structure extending into a body of water, which is designed to prevent shoaling of a channel by littoral materials and to direct and confine the stream or tidal flow. Jetties are built at the mouths of rivers or tidal inlets to help deepen and stabilize a channel.

KINETIC ENERGY (OF WAVES). In a progressive oscillatory wave, a summation of the energy of motion of the particles within the wave.

LAKESHORE. A general term used to denote the margin of the lake or a particular side of the lake. It does not refer to a specific area within the shorezone; the lakeside.

LEE. (1) Shelter, or the part or side sheltered or turned away from the wind or waves. (2) (Chiefly nautical) The quarter or region toward which the wind blows

LEEWARD. The direction *toward* which the wind is blowing; the direction toward which waves are traveling.

LENGTH OF WAVE. The horizontal distance between similar points on two successive waves measured perpendicularly to the crest.

LITTORAL. Of or pertaining to a shore.

LITTORAL CURRENT. See, CURRENT LITTORAL.

LITTORAL DEPOSITS. Deposits of littoral drift.

LITTORAL DRIFT. The sedimentary *material* moved in the littoral zone under the influence of waves and currents.

LITTORAL TRANSPORT. The *movement* of littoral drift in the littoral zone by waves and currents. Includes movement parallel (longshore transport) and perpendicular (on-offshore transport) to the shore.

LITTORAL TRANSPORT RATE. Rate of transport of sedimentary material parallel or perpendicular to the shore in the littoral zone. Usually expressed in cubic meters (cubic yards) per year. Commonly synonymous with LONGSHORE TRANSPORT RATE.

LITTORAL ZONE. In beach terminology, an indefinite zone extending lakeward from the shoreline to just beyond the breaker zone.

LOAD. The quantity of sediment transported by a current. It includes the suspended load of small particles and the bedload of large particles that move along the bottom.

LONGSHORE. Parallel to and near the shoreline; ALONGSHORE.

LONGSHORE BAR. A bar running roughly parallel to the shoreline.

LONGSHORE CURRENT. See CURRENT, LONGSHORE.

LONGSHORE TRANSPORT RATE. Rate of transport of sedimentary material parallel to the shore. Usually expressed in cubic meters (cubic yards) per year. Commonly synonymous with LITTORAL TRANSPORT RATE.

MASS TRANSPORT. The net transfer of water by wave action in the direction of wave travel.

MONOCHROMATIC WAVES. A series of waves generated in a laboratory; each wave has the same length and period.

NEARSHORE (zone). In beach terminology an indefinite zone extending lakeward from the shoreline well beyond the breaker zone. It defines the area of NEARSHORE CURRENTS.

NEARSHORE CURRENT SYSTEM. The current system caused primarily by wave action in and near the BREAKER ZONE; four main components comprise the system: the shoreward mass transport of water, longshore currents, lakeward return flow, including rip currents, and the longshore movement of the expanding heads of rip currents.

NOURISHMENT. The process of replenishing a beach. It may be brought about naturally by longshore transport, or artificially by the deposition of dredged materials.

OFFSHORE. (1) In beach terminology, the comparatively flat zone of variable width, extending from the breaker zone to the seaward edge of the Continental Shelf. (2) a direction lakeward from the shore.

OFFSHORE CURRENT. (1) Any current in the offshore zone. (2) Any current flowing away from shore.

ONSHORE. A direction landward from the lake.

ORBIT. In water waves, the path of a water particle affected by the wave motion. In deepwater waves the orbit is nearly circular, and in shallow water waves the orbit is nearly elliptical. In general, the orbits are slightly open in the direction of wave motion, giving rise to MASS TRANSPORT.

ORBITAL CURRENT. The flow of water accompanying the orbital movement of the water particles in a wave. Not to be confused with wave-generated LITTORAL CURRENTS.

ORTHOGONAL. On a wave-refraction diagram, a line drawn perpendicularly to the wave crests.

PARTICLE VELOCITY. The velocity induced by wave motion with which a specific water particle moves within a wave.

PERCOLATION. The process by which water flows through the interstices of a sediment. Specifically, in wave phenomena, the process by which wave action forces water through the interstices of the bottom sediment and which tends to reduce wave heights.

PHASE. In surface wave motion, a point in the period to which the wave motion has advanced with respect to a given initial reference point.

PHASE VELOCITY. Propagation velocity of an individual wave as opposed to velocity of a wave group.

PLANFORM. The outline or shape of a body of water as determined by the stillwater line.

PLUNGE POINT. (1) For a plunging wave, the point at which the wave curls over and falls. (2) The final breaking point of the waves just before they rush up on the beach.

POTENTIAL ENERGY OF WAVES. In a progressive oscillatory wave, the energy resulting from the elevation or depression of the water surface from the undisturbed level.

PROFILE, BEACH. The intersection of the ground surface with a vertical plane; may extend from the top of the dune line to the lakeward limit of sand movement.

PROPAGATION OF WAVES. The transmission of waves through water.

REFLECTED WAVE. That part of an incident wave that is returned lakeward when a wave impinges on a steep beach, barrier, or other reflecting surface.

REFRACTION (of water waves). (1) The process by which the direction of a wave moving in shallow water at an angle to the contours is changed: The part of the wave advancing in deeper water, causing the wave crest to bend toward alinement with the underwater contours. (2) The bending of wave crests by currents.

REFRACTION COEFFICIENT. The square root of the ratio of the distance between adjacent orthogonals in deep water to their distance apart in shallow water at a selected point. When multiplied by the SHOALING FACTOR and a factor for friction and percolation, this becomes the WAVE HEIGHT COEFFICIENT or the ratio of the refracted wave height at any point to the deepwater wave height. Also, the square root of the ENERGY COEFFICIENT.

REVETMENT. A facing of stone, concrete slabs, etc. built to protect a scarp, embankment, or shore structure against erosion by wave action or currents.

RIP CURRENT. A strong current flowing lakeward from the shore.

RUNNEL. A corrugation or trough formed in the foreshore or in the bottom just offshore by waves or currents.

SCOUR. Removal of underwater materials by waves and currents, especially at the base or toe of a shore structure.

SETUP, WAVE. Superelevation of the water surface over normal surge elevation due to onshore mass transport of the water by wave action alone.

SHALLOW WATER. (1) Commonly, water of such depth that surface waves are noticeably affected by bottom topography. It is customary to consider water of depths less than one-half the surface wavelength as shallow water. (2) More strictly, in hydrodynamics with regard to progressive gravity waves, water in which the depth is less than 1/25 the wavelength; also called VERY SHALLOW WATER.

SHOAL (noun). A detached elevation of the lake bottom, comprised of any material except rock which may endanger surface navigation.

SHOAL (verb) (1) to *become* shallow gradually. (2) to *cause* to become shallow. (3) to *proceed* from a greater to a lesser depth of water.

SHOALING COEFFICIENT. The ratio of the height of a wave in water of any depth to its height in deep water with the effects of refraction, friction, and percolation eliminated.

SHORE. The narrow strip of land in immediate contact with the lake, including the zone between high and low water lines. A shore of unconsolidated material is usually called a BEACH.

SHORELINE. The intersection of a specified plane of water with the shore or beach (e.g., the high water shoreline would be the intersection of the plane of mean high water with the shore or beach).

SIGNIFICANT WAVE. A statistical term relating to the one-third highest waves of a given wave group and defined by the average of their heights and periods. The composition of the higher waves depends upon the extent to which the lower waves are considered. Experience indicates that a careful observer who attempts to establish the character of the higher waves will record values which approximately fit the definition of the significant record values which approximately fit the definition of the significant wave.

SIGNIFICANT WAVE HEIGHT. The average height of the one-third highest waves of a given wave group. Note that the composition of the highest waves depends upon the extent to which the lower waves are considered. In wave record analysis, the average height of the highest one-third of a selected number of waves, this number being determined by dividing the time of record by the significant period.

SIGNIFICANT WAVE PERIOD. An arbitrary period generally taken as the period of the one-third highest waves within a given group. Note that the composition of the highest waves depends upon the extent to which the lower waves are considered. In wave record analysis, this is determined as the average period of the most frequently recurring of the larger well defined waves in the record under study.

SLOPE. The degree of inclination to the horizontal. Usually expressed as a ratio, such as 1:25 or 1 on 25, indicating 1 unit vertical rise in 25 units of horizontal distance; or in a decimal fraction (0.04); degrees (2° 18'); or percent (4%).

STILL-WATER LEVEL. The elevation that the surface of the water would assume if all wave action were absent.

STORM SURGE. A rise above normal water level on the open coast due to the action of wind stress on the water surface.

SUSPENDED LOAD. The material moving in suspension in a fluid, kept up by the upward components of the turbulent currents or by colloidal suspension.

SYNOPTIC CHART. A chart showing the distribution of meteorological conditions over a given area at a given time.

TROUGH OF WAVE. The lowest part of a waveform between successive crests. Also, that part of a wave below still-water level.

UPDRIFT. The direction opposite that of the predominant movement of littoral materials.

WATERLINE. A juncture of land and sea. This line migrates, changing with fluctuations in the water level. Where waves are present on the beach, this line is also known as the limit of backrush. (Approximately, the intersection of land and the still-water level.

WAVE. A ridge, deformation, or undulation of the surface of a liquid.

WAVE DIRECTION. The direction from which a wave approaches.

WAVE HEIGHT. The vertical distance between a crest and the preceding trough.

WAVE HEIGHT COEFFICIENT. The ratio of the wave height at a selected point to the deepwater wave height. The REFRACTION COEFFICIENT multiplied by the shoaling factor.

WAVE PERIOD. The time for a wave crest to traverse a distance equal to one wavelength. The time for two successive wave crests to pass a fixed point. See also SIGNIFICANT WAVE PERIOD.

WAVE PROPAGATION. The transmission of waves through water.

WAVE SPECTRUM. In ocean wave studies, a graph, table, or mathematical equation showing the distribution of wave energy as a function of wave frequency. The spectrum may be based on observations or theoretical considerations. Several forms of graphical display are widely used.

WAVE STEEPNESS. The ratio of wave height to wave length. (H/L).

WAVE TRAIN. A series of waves from the same direction.

WAVE TROUGH. The lowest part of a wave form between successive crests. Also that part of a wave below still-water level.

WAVELENGTH. The horizontal distance between similar points on two successive waves measured perpendicular to the crest.

WIND SETUP. On reservoirs and smaller bodies of water (1) the vertical rise in the still-water level on the leeward side of a body of water caused by wind stresses on the surface of the water; (2) the difference in still-water levels on the windward and the leeward sides of a body of water caused by wind stresses on the surface of the water. STORM SURGE (usually reserved for use on the ocean or large bodies of water).

WIND WAVES. (1) Waves being formed and built up by the wind. (2) Loosely, any wave generated by wind.

APPENDICES

APPENDIX A

DATA TABLES

Table 4. Site locations and measurement data

SITE LOCATIONS AND MEASUREMENT DATA

SITE NUMBER	SECTION LINE LOCATION	SURVEY ORIGIN	AIR PHOTO		YEAR OF MEASUREMENT			DISTANCE OT BLUFF CREST			
			NUMBER	DATE	GLO	BUCKLER	THIS STUDY	GLO	BUCKLER	THIS STUDY	
	BERRIEN COUNTY		ST JOSEPH								
2	North line/sec3/T5S,R19W	N 1/4 Cor	61	18 Apr 86	1829	1977	1986	1225.62	906.10	906.10	a.
3	South line/sec6/T4S,R18W	S 1/4 Cor	31	18 Apr 86	1830	1977	1986	2013.00	1830.65	1815.00	
4	North line/sec6/T4S,R18W	NE Cor	25	18 Apr 86	1830	1977	1986	1788.60	1156.78	1082.60	b.
5	South line/sec29/T3S,R18W	SE Cor	17	18 Apr 86	1830	1977	1986	2937.00	2507.10	2433.20	
6	South line/sec21/T3S,R18W	S 1/4 Cor	10	18 Apr 86	1830	1977	1986	1650.00	1301.71	1230.10	
	VAN BUREN COUNTY		SOUTH HAVEN								
7	South line/sec21/T1S,R17W	S 1/4 Cor	35	17 Apr 86	1830	1977	1986	1188.00	962.79	952.20	
8	South line/sec9/T1S,R17W	SE Cor	23	17 Apr 86	1830	1977	1986	995.94	600.90	575.10	
	ALLEGAN COUNTY		UNAVAILABLE								
11	South line/sec19/T2N,R16W	S 1/4 Cor			1831	1977	1986	1051.38	915.30	900.00	
12	South line/sec18/T2N,R16W	SE Cor			1831	1977	1986	2742.30	2608.58	2416.10	c.
13	South line/sec29/T2N,R16W	S 1/4 Cor			1831	1977	1986	1618.32	1481.45	1435.00	
14	South line/sec17/T3N,R16W	S 1/4 Cor			1831	1977	1986	2006.40	1871.28	1871.20	
	OTTAWA COUNTY		HOLLAND								
15	South line/sec16/T5N,R16W	S 1/4 Cor	47	17 Apr 86	1832	1977	1986	924.00	808.00	808.00	
16	South line/sec9/T5N,R16W	S 1/4 Cor	44	17 Apr 86	1832	1977	1986	891.00	858.40	785.70	
17	South line/sec4/T5N,R16W	S 1/4 Cor	34	17 Apr 86	1832	1977	1986	778.80	629.50	613.60	
18	South line/sec33/T6N,R16W	S 1/4 Cor	27	17 Apr 86	1832	1977	1986	754.38	653.90	477.80	
19	South line/sec28/T6N,R16W	S 1/4 Cor	21	17 Apr 86	1832	1977	1986	831.60	717.68	717.68	
			GRAND HAVEN								
20	South line/sec33/T7N,R16W	S 1/4 Cor	63	17 Apr 86	1832	1977	1986	1716.00	1660.22	1556.00	
21	South line/sec28/T7N,R16W	S 1/4 Cor	57/58	17 Apr 86	1832	1976	1986	2046.00	2084.41	2021.30	d.
22	South line/sec17/T7N,R16W	SE Cor	41	17 Apr 86	1832	1977	1986	429.00	283.30	278.30	e.
23	South line/sec32/T8N,R16W	S 1/4 Cor	24	17 Apr 86	1832	1977	1986	462.00	470.00	467.00	
	MUSKEGON COUNTY		MUSKEGON								
24	South line/sec8/T10N,R17W	S 1/4 Cor	3/4	29 Apr 85	1837	1977	1985	2539.80	2289.57	2228.30	
			WHITE LAKE								
28	South line/sec35/T12N,R18W	S 1/4 Cor	4	29 Apr 85	1837	1977	1985	1089.00	865.75	843.70	
29	South line/sec27/T12N,R18W	SE Cor	1	29 Apr 85	1837	1977	1985	224.40	21.50	15.00	

Table 4 (continued).

NOTES:

a. Buckler (1981) notes rapid bluff recession until 1971 when a steel pile and limestone block revetment across this point and extending north and south a considerable distance. Bluff recession has been minimal since 1971, therefor the recession rate is taken as the value established by Buckler in 1977.

b. The section line intersects the bluff where a large slump and some gullying have occurred. The long term recession rate for this site is probably higher than this reach of shore as a whole.

c. The section line coincides with the northern slope of a ravine through which intermittent drainage flows.

d. Buckler notes that although his survey reflects net accretion, comparison with a R.L.S. property survey indicated a bluff crest loss of 8.8 feet between 1974 and 1976.

e. Measurement was made to a line connecting the bluff crest on both sides of the section line. The crest was notched in 1973 with the installation of a drainage pipe.

1. Where air photos are unavailable, measurement was made by ground survey.

2. All measurements are in feet.

Table 5. Recession rates.

RECESSION RATES

	BLUFF CREST CHANGE			AVERAGE ANNUAL RECESSION RATE		
SITE NUMBER	GLO SURVEY TO 1976-77	1976-77 TO 1986	GLO SURVEY TO 1986	GLO SURVEY TO 1976-77	1976-77 TO 1986	GLO SURVEY TO 1986
2	-319.52	0.00	-319.52	-2.16	0.00	-2.16
3	-182.35	-15.65	-198.00	-1.24	-1.71	-1.27
4	-631.82	-74.18	-706.00	-4.30	-8.24	-4.53
5	-429.90	-73.10	-503.00	-2.92	-8.21	-3.20
6	-346.29	-73.71	-420.00	-2.39	-8.18	-2.69
7	-225.21	-9.79	-235.00	-1.53	-1.18	-1.51
8	-395.04	-25.80	-420.84	-2.69	-2.87	-2.76
11	-136.08	-15.03	-151.38	-0.93	-1.70	-0.98
12	-133.72	-192.48	-326.20	-0.92	-21.38	-2.10
13	-136.87	-46.45	-183.32	-0.94	-5.16	-1.18
14	-135.12	0.00	-135.12	-0.93	0.00	-0.87
15	-116.00	0.00	-116.00	-0.80	0.00	-0.75
16	-32.60	-72.70	-105.30	-0.22	-8.08	-8.68
17	-149.30	-16.00	-165.32	-1.03	-1.77	-1.07
18	-100.48	-176.10	-276.58	-0.69	-14.88	-1.52
19	-113.92	0.00	-113.92	-0.79	0.00	-0.74
20	-55.78	-104.22	-160.00	-0.38	-11.58	-1.04
21	+38.41	-63.41	-25.00	+0.27	-6.31	-0.16
22	-145.70	-5.30	-151.00	-1.00	-0.56	-0.98
23	+8.00	-2.70	+5.30	+0.06	-0.30	+0.03
24	-304.00	-61.50	-365.50	-2.17	-6.81	-2.47
28	-223.25	-22.05	-245.30	-1.59	-2.45	-1.66
29	-202.90	-6.50	-209.40	-1.45	-0.72	-1.41

NOTE: Bluff crest change values are given in feet and average annual recession rates are given in feet/year.

Table 6. Spring wave data.

SPRING WAVE DATA

HINDCAST POINT	SITE NUMBER	SPRING WAVE HEIGHTS AND PERIODS									
		5 YEAR		10 YEAR		20 YEAR		50 YEAR		100 YEAR	
		HT.	PER.	HT.	PER.	HT.	PER.	HT.	PER.	HT.	PER.
26		8.9	7.1	9.8	7.8	11.6	8.4	13.5	8.9	15.2	9.3
	2	8.8	7.6	9.8	7.8	11.6	8.4	13.5	8.9	15.2	9.3
	3	8.7	7.6	9.9	7.9	11.4	8.3	13.5	8.8	15.0	9.1
	4	8.6	7.5	9.9	7.9	11.4	8.3	13.5	8.8	15.0	9.1
	5	8.6	7.5	9.9	7.9	11.4	8.3	13.5	8.7	15.0	9.1
	6	8.5	7.5	9.9	7.9	11.3	8.2	13.5	8.7	14.9	9.0
25		8.5	7.5	9.9	7.9	11.3	8.2	13.5	8.7	14.9	9.0
24		8.9	7.5	9.8	7.7	11.9	8.4	14.5	9.1	16.2	9.6
	7	8.9	7.5	9.8	7.7	12.0	8.4	14.9	9.2	16.7	9.7
	8	8.9	7.5	9.8	7.7	12.2	8.4	15.2	9.3	17.3	9.9
23		8.9	7.4	9.8	7.6	12.6	8.5	16.2	9.6	18.8	10.3
	11	9.2	7.3	10.2	7.5	12.4	8.1	15.6	9.2	18.4	10.0
	12	9.4	7.3	10.4	7.5	12.4	8.1	15.2	8.9	17.5	9.4
	13	9.6	7.2	10.8	7.4	12.3	7.9	14.6	8.4	16.7	8.8
22		9.8	7.2	10.9	7.4	12.2	7.7	14.2	8.1	16.2	8.5
	14	9.8	7.2	10.9	7.4	12.2	7.7	14.2	8.1	16.2	8.5
21		9.8	7.8	11.9	8.3	13.5	8.7	15.8	9.2	17.5	9.7
	15	9.8	7.8	11.8	8.3	13.4	8.7	15.7	9.3	17.4	9.7
	16	9.8	7.8	11.8	8.3	13.4	8.7	15.7	9.3	17.4	9.7
	17	9.8	7.8	11.8	8.3	13.4	8.7	15.7	9.3	17.4	9.7
	18	9.8	7.8	11.7	8.3	13.3	8.8	15.6	9.3	17.3	9.6
	19	9.8	7.8	11.7	8.3	13.3	8.8	15.6	9.3	17.3	9.6
20		9.8	7.8	11.6	8.3	13.2	8.8	15.5	9.4	17.2	9.6
	20	9.9	7.8	11.6	8.3	13.2	8.8	15.4	9.4	17.0	9.6
	21	10.0	7.9	11.6	8.3	13.1	8.8	15.1	9.3	16.7	9.5
	22	10.2	8.0	11.6	8.3	12.9	8.7	14.7	9.1	16.3	9.4
	23	10.5	8.1	11.6	8.3	12.7	8.6	14.1	8.9	15.5	9.3
19		10.6	8.1	11.6	8.3	12.6	8.5	13.8	8.8	15.2	9.2
18		10.5	8.0	11.5	8.3	12.6	8.5	13.8	8.8	15.5	9.4
	24	10.5	8.0	11.5	8.3	12.7	8.5	14.0	8.8	15.8	9.4
17		10.5	7.9	11.5	8.1	13.2	8.4	14.9	8.9	17.5	9.4
	28	10.5	8.0	11.5	8.2	13.1	8.5	14.7	8.9	16.9	9.4
	29	10.5	8.0	11.5	8.2	13.1	8.5	14.7	8.9	16.8	9.4
16		10.5	8.1	11.5	8.3	12.8	8.7	14.1	9.0	15.1	9.3

NOTE: Wave heights are given in feet and wave periods are given in seconds.

Table 7. Fall wave data.

FALL WAVE DATA

HINDCAST POINT	SITE NUMBER	FALL WAVE HEIGHTS AND PERIODS									
		5 YEAR		10 YEAR		20 YEAR		50 YEAR		100 YEAR	
		HT.	PER.	HT.	PER.	HT.	PER.	HT.	PER.	HT.	PER
26		14.8	9.2	15.7	9.4	16.4	9.6	18.1	10.0	19.8	10.5
	2	14.8	9.2	15.7	9.4	16.4	9.6	18.2	10.0	19.9	10.5
	3	14.8	9.1	15.7	9.3	16.6	9.5	18.5	10.0	20.4	10.5
	4	14.8	9.1	15.7	9.3	16.6	9.5	18.6	10.0	20.5	10.5
	5	14.8	9.0	15.7	9.2	16.6	9.5	18.7	10.0	20.6	10.5
	6	18.4	9.0	15.7	9.2	16.7	9.4	18.7	10.0	20.7	10.5
25		14.8	9.0	15.7	9.2	16.7	9.4	18.8	10.0	20.8	10.5
24		15.4	9.3	16.1	9.5	17.1	9.8	18.8	10.2	20.8	10.8
	7	15.4	9.3	16.1	9.5	17.1	9.8	19.1	10.3	21.1	10.9
	8	15.4	9.3	16.1	9.5	17.1	9.8	19.4	10.4	21.4	11.0
23		15.4	9.3	16.1	9.5	17.1	9.8	20.1	10.7	22.1	11.2
	11	15.4	9.0	16.3	9.2	17.4	9.5	19.9	10.0	21.7	10.6
	12	15.4	8.9	16.4	9.1	17.6	9.4	19.9	10.0	21.5	10.3
	13	15.4	8.6	16.6	8.8	17.8	9.2	19.8	9.7	21.2	9.9
22		15.4	8.4	16.7	8.6	18.0	9.0	19.7	9.3	21.0	9.6
	14	15.4	8.4	16.7	8.6	18.0	9.0	19.7	9.3	21.0	9.6
21		15.7	9.2	16.7	7.9	17.7	9.7	19.4	10.1	20.3	10.4
	15	15.7	9.2	16.8	8.3	17.9	9.8	19.7	10.3	20.6	10.5
	16	15.7	9.2	16.8	8.3	17.9	9.8	19.7	10.3	20.6	10.5
	17	15.7	9.3	16.9	8.8	18.2	10.0	20.0	10.4	21.1	10.8
	18	15.7	9.3	16.9	8.9	18.2	10.0	20.1	10.5	21.2	10.8
	19	15.7	9.3	16.9	9.0	18.3	10.1	20.2	10.5	21.3	10.9
20		15.7	9.4	17.1	9.6	18.7	10.3	20.7	10.8	22.0	11.2
	20	15.8	9.4	17.2	9.6	18.8	10.3	20.7	10.8	22.1	11.2
	21	15.9	9.4	17.3	9.7	18.9	10.3	20.8	10.8	22.2	11.2
	22	16.2	9.5	17.5	9.7	19.0	10.3	21.0	10.8	22.5	11.2
	23	16.6	9.6	17.9	9.9	19.3	10.2	21.2	10.8	22.9	11.2
19		16.7	9.6	18.0	9.9	19.4	10.2	21.3	10.8	23.0	11.2
18		16.4	9.6	18.0	10.0	19.7	10.6	22.0	11.3	23.6	11.7
	24	16.4	9.6	18.0	10.0	19.7	10.6	21.9	11.2	23.5	11.5
17		16.1	9.1	17.8	9.5	19.4	9.9	21.3	10.4	23.0	10.7
	28	16.1	9.2	17.7	9.6	19.6	9.8	21.1	10.6	22.7	10.9
	29	16.1	9.3	17.7	9.7	19.6	9.8	21.1	10.6	22.7	10.9
16		16.1	9.6	17.4	10.0	18.7	10.3	20.7	10.8	22.0	11.2

NOTE: Wave heights are given in feet and wave periods are given in seconds.

Table 8. Hindcast and site locations/nearshore slope.

HINDCAST / SITE LOCATIONS AND NEARSHORE SLOPE

HINDCAST POINT	SITE NUMBER	LATITUDE		NEARSHORE SLOPE 1:X
		DECIMAL	DEG/MIN/SEC	
26		42.06	42 03 36	
	2	42.08	42 04 55	113.64
	3	42.15	42 08 50	120.48
	4	42.17	42 10 06	95.24
	5	42.18	42 10 32	97.09
	6	42.19	42 11 17	93.46
25		42.21	42 12 36	
24		42.34	42 20 24	
	7	42.37	42 21 58	125.00
	8	42.40	42 23 52	111.11
23		42.48	42 28 48	
	11	42.54	42 32 08	93.46
	12	42.56	42 33 23	100.00
	13	42.61	42 36 44	91.74
22		42.64	42 38 24	
	14	42.64	42 38 37	169.49
21		42.78	42 46 48	
	15	42.81	42 48 45	94.34
	16	42.81	42 48 48	108.70
	17	42.85	42 50 43	96.15
	18	42.86	42 51 32	91.74
	19	42.87	42 52 19	103.09
20		42.93	42 55 48	
	20	42.94	42 56 33	86.96
	21	42.96	42 57 44	77.52
	22	42.99	42 59 18	100.00
	23	43.04	43 02 19	101.01
19		43.06	43 03 36	
18		43.23	43 13 48	
	24	43.25	43 15 00	83.33
17		43.36	43 21 36	
	28	43.40	43 23 45	125.00
	29	43.41	43 24 31	111.11
16		43.52	43 31 12	

APPENDIX B

VARIABLES AND EQUATIONS

VARIABLE NOTATION

H_o = deepwater waveheight (ft)

T = wave period (seconds)

θ_o = deepwater wave angle (angle wave crest makes with the bottom contours in degrees)

ρ = water mass density (1.94 slugs/ft^3 for fresh water)

h = water depth of interest (ft)

z = distance of interest below still water level (ft)

m = average slope of lake bed

L_o = deepwater wavelength (ft)

c_o = deepwater phase velocity (ft/sec)

c_{go} = deepwater group velocity (ft/sec)

H = wave height (ft)

L = wavelength (ft)

c = wave phase velocity (ft)

c_g = wave group velocity (ft)

θ = angle of approaching wave crests with bottom contours (degrees)

K_s = shoaling coefficient

K_r = refraction coefficient

U = Ursell parameter

E = mean energy density (ft-lbs/ft^2)

P = mean energy flux (ft-lbs/ft-sec)

Δh = setdown (ft)

u_{max} = maximum horizontal water particle velocity (ft/sec)

w_{max} = maximum vertical water particle velocity (ft/sec)

P_z = total pressure (lbs/ft^2)

H_b' = breaking height (ft)

h_b = depth at breaking (ft)

P_{ls} = longshore energy flux (ft-lbs/ft-sec)

g = gravitational acceleration (32.17 ft/sec^2)

LIST OF EQUATIONS

$L_o = gT^2/2\pi$

$c_o = L_o/T$

$c_{go} = 1/2\ c_o$

$H = H_o K_s K_r$

$w = 2\pi/T$

$k = 2\pi/L$

$\omega^2 = gk \tanh kh$

$c = (gT/2\pi)(\tanh(kh))$

$c_g = 1/2\ c(1+G)$

$G = 2kh/\sinh 2kh$

$\Theta = \sin^{-1}[(c/c_o)\sin \Theta_o]$

$K_s = (c_o/2c_g)^{1/2}$

$U = HL^2/h^3$

$E = 1/8(\rho g H^2)$

$P = Ec_g$

$$\Delta h = GH^2/16h$$

$$u_{max} = (HgT/2L)(\cosh[2\pi(z+h)/L])/(\cosh[2\pi h/L])$$

$$w_{max} = (HgT/2L)(\sinh[2\pi(z+h)/L])/(\cosh[2\pi h/L])$$

$$P_z = \rho h(H/2)(\cosh k[z+h]/\cosh kh) - \rho gz$$

$$P_{ls} = (\rho g/16)(H^2 c_g \sin 2\theta)$$

$$H = H_o K_s k_r$$

$$K = b - aH_b/gT^2$$

$$b = 1.56/(1+e^{-19.5ft})$$

$$a = 43.8(1-e^{-19ft})$$

$$h_b = H_b/k$$

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