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RATES AND IMPLICATIONS OF BLUFF RECESSION ALONG THE LAKE MICHIGAN SHOREZONE OF MICHIGAN AND WISCONSIN

Michigan State University PH.D. 1981

RATES AND IMPLICATIONS OF BLUFF RECESSION ALONG THE LAKE MICHIGAN SHOREZONE OF MICHIGAN AND WISCONSIN

By

William Roger Buckler

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ABSTRACT

RATES AND IMPLICATIONS OF BLUFF RECESSION ALONG THE LAKE MICHIGAN SHOREZONE OF MICHIGAN AND WISCONSIN

By

William Roger Buckler

Long-term Lake Michigan bluff crest recession rates at 118 widespread locations in Michigan and Wisconsin are determined by contrasting recent field measurements with those from 19th century government land office surveys. These rates are evaluated spatially and related to selected shorezone characteristics. In addition, lake level records and aerial photographic data are compared to determine recent recession rates at closely spaced case study sites in Shoreham, Michigan, and Kenosha County, Wisconsin; these provide a basis for predicting future bluff crest positions.

Long-term recession data indicate that: (1) Sites and segments on both sides of Lake Michigan display wide variability in bluff line changes. (2) Bluff crest recession along opposite shores is statistically similar. (3) Non-sand dune bluffs along the southern shore of each state tend to experience relatively rapid retreat. (4) Bluffs in southern Wisconsin recede at rates significantly higher than those in the north.

Findings based on the 118 sites also reveal that: (1) Bluffs of dune sand tend to recede at significantly lower long-term rates than bluffs composed of non-dune sediments; apparently these lower values result from dune accretion during periods of low lake level. (2) Variations in long-term recession rates of bluffs composed of non-eolian material are not directly related to differences in sediment type or arrangement. (3) Differences in shoreline orientation and fetch appear to influence rates of retreat. (4) Long-term recession rates do not vary directly with changes in bluff height or ground water activity even though the latter may contribute to slope instability, especially on high bluffs.

Results of the two case studies disclose that: (1) Modern recession rates vary according to the interval between measurements. (2) The highest rates tend to occur within periods that contain the greatest percentage of years when lake levels are high. (3) Modern rates are not similar to long-term retreat values, a condition largely attributable to increasing numbers of shore protection structures that may accelerate bluff retreat in some places.

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Numerous individuals assisted me in the successful completion of this dissertation. Two people are especially noteworthy. I am extremely grateful to Dr. Harold A. "Duke" Winters, my major advisor, who somehow endured through it all. His guidance, patience, time (measured on the geologic scale), constructive criticism, "better words," and instructional methods are greatly appreciated. (But a kick in the pants occasionally would not have hurt either.) I am a better geographer because of him.

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AMEN and THE END! (Duke, there are no "better words.")

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Chapter 1

OBJECTIVES, METHODOLOGY AND LITERATURE REVIEW

Introduction

Bluffs of unconsolidated sediments along much of the Lake Michigan shorezone[1] have experienced significant recession; for some segments of the lakeshore bluff crest retreat may be in the magnitude of several miles[2] in the last 4,000 years (Andrews, 1870; Maxwell, 1919; Niendorf, et al., 1967) and, in places, losses of over 1,000 feet in the last 140 years are substantiated. Erosion of these bluffs is of increasing concern due to intensified occupation and generally high land values along the lakeshore. Storm systems moving over the water, especially in fall and spring, may generate waves that erode the shoreland. Beaches, which tend to be relatively wide during low water elevations and thus provide protection for the shorezone bluffs, may decrease in width or even disappear due to inundation with rising lake levels. Since 1875 the level of Lake Michigan has varied 6.5 feet in elevation and there have been nine periods, ranging from one to 20 years, when average annual water levels have been above the mean; during these times storm waves more readily reach and erode the base and

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[1] Lakeshore terminology used in this study is defined in Appendix A and shorezone features are illustrated in Figure 2 of Chapter 2.

[2] Metric equivalents are shown in parentheses only for precise bluff recession measurements.

subsequently the crest of the bluff.[3] Accelerated erosion may continue following lake level subsidence until denuded slopes stabilize and become revegetated.

Objectives

This study has three basic objectives:

(1) To determine long-term bluff crest recession at a number of sites along the Michigan and Wisconsin lakeshores and to compare these findings with selected characteristics of the shorezone.

(2) To test the hypothesis that within the segments examined bluff crest recession is greater on the eastern side of the lake. Most shorezone erosion is thought to be attributed to wave erosion during intensive fall and spring cyclonic storms (Seibel, 1972; Davis, Seibel, and Fox, 1973). Because a major component of the storms involves an easterly movement it may be that the bluffs on the east side of the lake recede at a faster rate since westerly winds tend to have higher velocities and may be of longer duration than those from the east. Limited studies (Saville, 1953; Davis and Fox, 1974) indicate that a greater amount of deep water storm wave energy is transmitted toward the Michigan shore than toward the Wisconsin lakeside.

(3) To investigate two areas in detail and to predict future bluff crest positions and suggest possible consequences resulting from retreating bluffs at these locations.

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[3] Although waves are the major agents of erosion, other factors may play important roles in bluff recession.

Study Areas

This investigation focuses on selected sites along two segments of the Lake Michigan shorezone: these extend from (1) the Illinois-Wisconsin state line northward to the Sturgeon Bay Canal in Door County, Wisconsin, and (2) from the Indiana-Michigan border northward to the northern tip of the Leelanau Peninsula in Leelanau County, Michigan (Figure 1). These areas consist of unconsolidated Pleistocene and Recent sediments and represent about 74% of the total Lake Michigan shoreland designated as being subject to erosion. Approximately 88% of those lakeshore segments identified as critical erosion areas[4] by the Corps of Engineers (U.S. Army Corps of Engineers, 1971a) are within the study areas.

Basic Criteria

Study sites are from selected locations where U.S. Public Land Survey section lines intersect the Lake Michigan bluff. It is at these places where long-term changes in bluff crest position can be determined by comparing measurements available in the original General Land Office (GLO) survey notes[5] with more recent surveys. In addition, field measurements taken in 1957 (Powers, 1958) are available for many of these sites; these provide a basis for the determination of short-term changes (1957 to 1976-77) in bluff positions.

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[4] Critical erosion areas are defined as those reaches of shoreline having existing high value economic and recreational resources and a historic record of rapid loss of land and/or structural damage. All other shoreline reaches recording erosion damage are classified as noncritical erosion areas (U.S. Army Corps of Engineers, 1971a, p. 3).

[5] The original GLO surveys in the Michigan and Wisconsin study areas were conducted between 1827 and 1852.

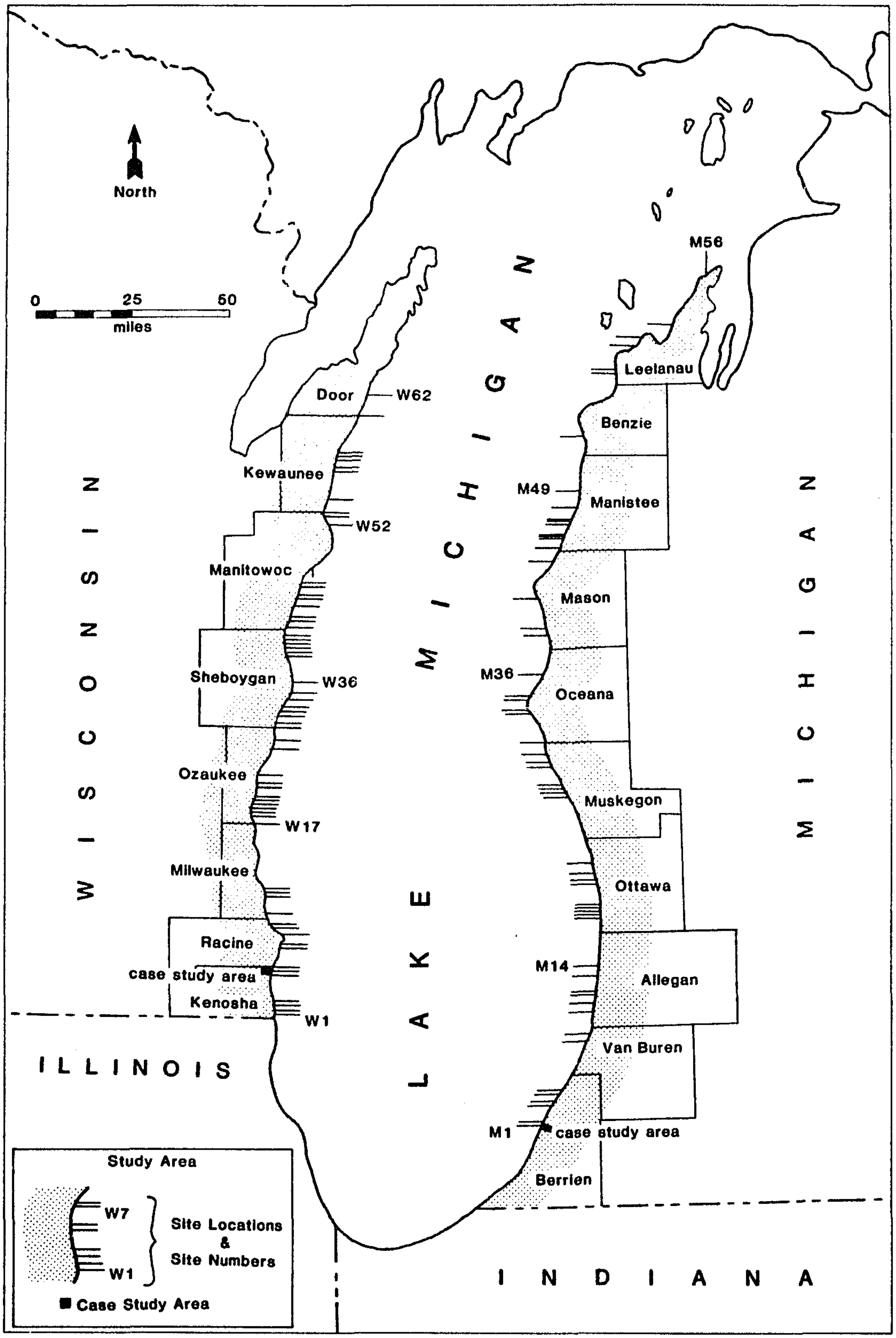

Figure 1. Study areas and site locations.

Only sites where shorezone bluffs exist are considered in this study. 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.

Except for the case study areas, bluff top changes were determined on the basis of field measurements during the field seasons of 1976 and 1977 by utilizing standard surveying techniques.[6]

Description and Use of the General Land Office Surveys

In practially all instances the original GLO surveys of Michigan and Wisconsin represent the earliest quantitative records of the Lake Michigan bluff line position. Distances from section and quarter section corners within a mile of the lake to the Lake Michigan "meander line" are recorded in the GLO notes. According to Powers (1958, pp. 89-90) "the 'meander line' was never precisely defined, but clearly it was seldom, if ever, identified with the water line. In many cases the measurements were obviously made to some point at or near

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[6] This is contrary to most recent studies of the Lake Michigan shorezone. The extensive shoreland reaches, budget problems, and personnel limitations have resulted in the increasing use of aerial photogrammetric methods in determining bluff losses and gains.

the edge of the bluff, where present."[7] For sites selected in this investigation it is assumed that the meander line represented the lakeward bluff crest and all resurveys were conducted accordingly.[8] Some sites where measurements are feasible were eliminated from this study because of the questionable relationship between the meander line and the bluff crest. It is possible that bluff recession determined for some of the 118 sites may be in error. But if errors do exist they are believed to be very few and the large number of sites with appropriate data provide a sound basis for analysis.

By resurveying and comparing these section line distances with the GLO measurements long-term and average annual bluff top changes can be ascertained at places where the section line intersects the lakeshore bluff. In a few cases, however, calculated losses or gains may "be somewhat less [or more] than the actual wherever the original meander line was inland from the bluff edge" (Powers, 1958, p. 90).

Surveying Procedures

Information was obtained from local surveyors, registers of deeds and/or road commissioners or engineers concerning recorded witnesses to desired section corner locations and previously conducted

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[7] Breed, Hosmer, and Bone (1970, p. 162) indicate that the meander line may be found at the top of an escarpment formed by wave erosion.

[8] Previous Lake Michigan shorezone researchers have usually equated the meander line with the crest of the bluff where one exists (Chamberlin, 1877; Powers, 1958; Seibel, 1972; Jannereth, 1975; among others). For example, in all of the Corps of Engineers' erosion control studies conducted within the study areas the original survey distances from the section corners to the meander line, and all subsequent resurveys, were identified as being from "section corner" to "bluff crest" (U.S. Army Corps of Engineers, 1946, 1953, 1955, 1958, 1975).

lot or subdivision measurements that were run along the section lines toward the lake. Commonly these surveys provided a previously measured distance from the section corner to a survey marker on the line; consequently, only the remaining distance to the bluff top had to be measured. 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[9] fairly accurately (within three to five feet).

All measurements to the bluff followed as closely as possible to the true bearing of the section line. If two points known to be on the section line were found, the line between them established the bearing. In other cases it was assumed that the section line coincided with the center line of a road or a fence row. At the few locations where the survey lines are not apparent, measurements were made along an east-west trend.

Distances along the section line were established by using a 100-foot engineer's steel tape and/or by stadia method utilizing a transit and Philadelphia and/or stadia rod (for short and long distances, respectively); standard surveying procedures were followed (Davis, Foote, and Kelley, 1966; Brinker, 1969; Breed, Hosmer, and Bone, 1970). Some distances were obtained from previously performed surveys by registered land surveyors (R.L.S.). The probable error in measurement ranged from one foot in 5,000 feet for the R.L.S. distances to an error of approximately 0.25% or less for the stadia method.

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[9] Fence lines and roads commonly coincide with boundaries of the land survey system.

All measurements were to the crest of the lakeshore bluff. In places where pedestrian or vehicular traffic had notched sags in the bluff's upper boundary so that an abrupt departure in slope was not evident, the resurvey was carried to an imaginary line connecting the bluff edge on either side of the site line. At locations where the bluff crest was rounded a somewhat arbitrary edge position was established, resulting in an estimated error of less than three feet.

Site Selection

All section lines intersecting Lake Michigan within the study areas were investigated. Of those where bluffs exist 118 were resurveyed, 56 in Michigan and 62 in Wisconsin (Figure 1).[10] For each of these long-term changes in bluff position were computed on the basis of comparison with the GLO surveys.

Site Observations

The following conditions were examined at each site:

(1) Bluff Composition. Sediments comprising the bluff profile were examined, hand textured, and categorized according to the U.S.D.A.

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[10] At all other locations problems were encountered and the potential sites had to be eliminated. These problems were related to one or more of the following:

(a) the lack of confidence in the original GLO survey measurement;
(b) the inability to relocate appropriate survey corners or to retrace the original survey line to the lake bluff;
(c) alteration of the lakeshore bluff edge by pedestrian and/or vehicular traffic;
(d) the existence of structures, drains, and/or artificial fill in the shorezone;
(e) the nature of the bluff composition and profile (especially in the sand dune areas); and
(f) the lack of a definable bluff.

soil textural triangle classes (Soil Survey Staff, 1951). Modifiers of class names were used to indicate the presence of particles greater than 2 mm. The genesis of the material was indicated if such a determination could be made. If overburden covered all or part of the bluff face the nature of the sediment(s) was frequently determined by inspecting exposures adjacent to the site line.

(2) Bluff Height. Bluff height was usually established by hand level but occasionally it was necessary to utilize topographic maps.

(3) Shoreline Orientation. The trend of the shoreline was determined from U.S.G.S. topographic maps by measuring the bearing of a line tangent to the shore from a point one-quarter mile southward to one-quarter mile northward of the section line.

(4) Ground Water and Artificial Drainage. Where possible the presence of artificial drains and evidence of ground water seeps within the bluff slope were noted in the vicinity of the section line site; it is likely, however, that many were overlooked because of the intermittent nature of the seeps or burial by mass-wasted material.

(5) Beach Width. Beach width was determined by pacing. It is apparent, though, that the character and influence of the beach may vary with changes in such variables as lake level, shorezone structures, wave orientation, and weather conditions.

(6) Shorezone Structures. All structures in the vicinity of the section line were noted and their apparent influence on the shorezone recorded.

(7) Bluff Stability. An appraisal of bluff stability was made at each site; of particular interest was evidence of mass-movement on the slope. Furthermore, conditions and processes occurring between and at the bluff base and the crest were noted.

(8) Photo Record. Photographs were taken of both beach and bluff top condition at the section line site and vicinity. These were helpful during data analysis and may prove useful for future studies.

Literature Review

Erosional problems along the shore of Lake Michigan in Wisconsin and Michigan were recognized as early as the middle 1800's by Lapham (1847). Later in the century Whittlesey (1867), Andrews (1870), Chamberlin (1877), Woolridge (1884), and Leverett (1899) also directed attention to such conditions. Numerous subsequent references show that erosion has continued to be a serious concern to many localities, especially during periods of high water elevations (Maxwell, 1919; Ball, 1920, 1938; Wojta, 1945; Brater, 1950a; Granger, 1957; Pincus, 1962; Seibel, 1972; Davis, Seibel, and Fox, 1973; Consoer, Townsend, and Associates, 1973; Hadley, 1976; Mickelson, et al., 1977; among many). The literature has focused on various aspects of the problem. For example, some authors have published data on rates of lakeshore bluff recession, others have related shorezone erosion to specific processes and/or variables, whereas still others have dealt with protection and management of the shorezone or were concerned only with disseminating general information about lakeshore conditions.

Shoreland erosion losses have been ascertained by numerous investigators. Some have determined rates of retreat by actual field survey methods (Andrews, 1870; Chamberlin, 1877; Leverett, 1899; Ball and Powers, 1930; Powers, 1958; Davis, 1971, 1972, 1973, 1976; Davis and Fingleton, 1972, 1973; Fingleton, 1973; Davis, Fingleton, and Pritchett, 1975; Buckler, 1973; Buckler and Winters, 1975; and Maresca, 1975). Commonly these recession rates were calculated for locations coinciding with section lines; distances recorded in the original land survey notes along these lines provide a base to which more recent measurements can be compared. Of special interest is the project by Powers (1958). He resurveyed 134 section line locations and calculated average annual losses or gains for each site; 106 of these are within the present study areas. Other researchers have relied on measurements from aerial photography to ascertain rates of shoreland retreat (U.S. Army Corps of Engineers, 1946, 1953, 1957, 1958, 1975; Farrand, 1970; Seibel, 1972; Brater and Seibel, 1973; Frankovic, 1975; and the present Michigan Department of Natural Resources shoreline erosion program). Keillor and DeGroot (1978) ascertained bluff recession rates along the Racine County, Wisconsin, shore by comparing two sets of 1:2,400-scale topographic maps compiled from specially flown aerial photography.

Seibel, Armstrong, and Alexander (1976) have compiled into one publication all available recession rate data from various agencies, individuals, and previous reports. For each shoreline reach for which data are available they have estimated a weighted average annual, maximum annual, and minimum annual recession rate. Monteith and Sonzogni (1976; see also Monteith, 1977, and Sonzogni, Monteith, and Seibel, 1978) utilized much of the raw data of the aforementioned report to estimate the volume of material eroded and to determine whether shore erosion is likely to be a significant pollutant source to the Great Lakes.

Chamberlin (1877), Powers (1958), Seibel (1972), Buckler (1973), Buckler and Winters (1975), and Seibel, Armstrong, and Alexander (1976) determined that bluff erosion rates are not uniform at selected shoreline sites nor can they be anticipated to be similar at sites with similar characteristics during two or more distinct time periods. Davis (1971; 1972; 1973; 1976), Davis and Fingleton (1972; 1973), Fingleton (1973), and Davis, Fingleton, and Pritchett (1975) found a lack of correlation between beach profile changes at adjacent sites even though observed characteristics were similar. Whittlesey (1867) observed that in southwestern Michigan promontories were eroding faster than bays or curves in the shoreline, thus giving the lake a more regular outline.[11]

Goldthwait (1907), Alden (1918), and Ball (1920; 1938) indicated that bluff recession has been rapid enough along parts of the present lake to truncate many ancestral Lake Michigan shoreline features. Lapham (1847), Goldthwait (1908), Alden (1918), Ball (1920), and Thwaites (1931) discussed the process of "intercision" whereby bluff retreat along the Wisconsin shore had intercepted bends in streams generally paralleling the lake so that their valleys presented three openings to Lake Michigan instead of the normal one.

As early as 1867 Whittlesey realized the importance of lake level elevation to shoreline erosion, which tends to be accelerated during high levels and diminished during lower water periods. Goldthwait (1907), Ball and Powers (1930), and Kingery (1944), among others, published recession rates for a number of sites to emphasize this point. Although Seibel (1972) "quantitatively established" a positive relationship between mean annual lake levels and the average rate of bluff line retreat, Davis, Seibel, and Fox (1973, p. 406) stressed that "high lake levels play a passive role in that they 'allow' erosion to take place at a rapid rate; they do not 'cause' it to do so."

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[11] Interestingly, Carter (1975, p. 163) recently pointed out that the present Lake Erie shoreline is getting more irregular, basically due to disruption of the longshore drift of sand.

Following intensive study of successive high water cycles along part of the Illinois high bluff shoreline, Berg and Collinson (1976; Collinson and Berg, 1976) suggested several generalizations concerning bluff recession along Lake Michigan: (1) Significant bluff recession begins once the lake has exceeded a level of 579 feet, especially if protective structures are lacking and littoral drift is minimal, and even if well-developed beaches exist. (2) Falling lake levels do not necessarily signify immediate decrease in bluff recession because time is required for revegetation of the denuded slopes. (3) Maximum erosion may be delayed during rising lake levels until previously built beaches are degraded. Davis (1976), however, suggests that the critical level along the eastern shore of the lake is 580 feet; and above this elevation erosion occurs everywhere.

Recently three Lake Michigan studies tested variations of the "Brunn effect."[12] Larsen (1973, p. 67) theorized that "given similar bluff height and composition, the retreat of the base of the bluff is in direct proportion to the water levels to which it is exposed." His findings, however, indicated a one to tenfold variation in this anticipated relationship. He partially attributed this contradiction to erection of man-made structures along the shore. Tanner (1975) reasoned that "a significant rise in lake level should be accompanied and followed by an important increase in beach erosion; much or most of the sand eroded should be carried offshore rather than in the littoral drift system." He reports that this "theoretical projection is

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[12] Brunn (1962; Schwartz, 1976) believes that as sea level rises the sediments eroded from the upper beach should be deposited in equal volume in the nearshore zone; the resulting rise in the nearshore bottom should correspond directly with the rise in the water level.

confirmed" along the Berrien County, Michigan, shore. DuBois (1976) reported that the Brunn effect is applicable in the zone of the first longshore bar system in Lake Michigan at Terry Andrae State Park, Sheboygan County, Wisconsin.

Early observers, such as Lapham (1847) and Woolridge (1884), recognized that significant shorezone erosion occurred during storm conditions. Seibel's (1972, p. 138) "investigation produced no correlation between the average number of cyclones and average rate of erosion-average lake level," suggesting "that it is not the total number of storms but rather the larger isolated storms that have a greater bearing on the rate of erosion." The recent beach and nearshore environment studies by Fox and Davis (1970a, 1970b, 1971a, 1971b, 1973a, 1973b; Davis and Fox, 1971, 1972a, 1972b; Davis, 1976) along the eastern shore of Lake Michigan also indicate that it is during intense storms of short duration when the most severe erosion is likely to take place, although erosion rates along the shore may vary considerably during a single storm. They believe that local variations in erosion are largely due to "subtle differences in nearshore topography" (Davis, Seibel, and Fox, 1973, p. 408). The amount of wave energy available at a given location depends on the position and depth of longshore sand bars in the nearshore zone.

More recently Keillor and DeGroot (1978) characterized the storm wave energy eroding the Racine County, Wisconsin, shoreline between 1968-1976. They believe that irregular offshore bottom features, and especially reef structures, influence the direction of incoming waves and cause a complex pattern of wave energy diffusion and concentration along the shore.

Maresca (1975) measured bluff line recession and beach and nearshore changes attributable to the passage of nine individual storms along a three-kilometer sandy stretch in southwestern Michigan. He observed a rhythmic pattern within the shoreline segment and recognized three distinctive length scales under which the spatial distribution of bluff line recession operated.

> The largest length scale was attributed to the convergence and divergence of wave energy by refraction. The middle length scale was attributed to the unequal distribution of breaker heights in the nearshore zone and the smallest scale was the result of the unequal failure of the bluff.

Conflicting opinions have been expressed as to the relationships between bluff lithology and recession rates. Alden (1918, p. 338) reported that "where much sand and soft clay occur...erosion is easy and the bluff recedes rapidly." Chieruzzi and Baker (1959, p. 114) noted that "the material present in the bluff will control, to a great extent, the rate of recession." Likewise, Wilkinson and Gray (1978) suggest that lateral variations in lithology of the drift are directly correlative with spatial variations in recession rates along a 10-kilometer stretch of Lake Michigan near Glenn, Michigan. Davis, Seibel, and Fox (1973, p. 407), however, found that, at selected sites along the eastern Lake Michigan shore, recession "rates show no pattern that may be correlated with coastal composition." A similar conclusion was reached by Buckler (1973; Buckler and Winters, 1975), at least on a long-term (approximately 140 years) basis. Results of a three-year beach profile study also along the eastern reach of Lake Michigan indicate that "bluffs composed of till eroded at only one-half the rate of predominantly sandy bluffs or dunes" (David, Fingleton, and Pritchett, 1975, p. 57). Seibel (1972), nonetheless, reported that clay till bluffs retreated at a higher rate than sand bluffs during a downward trend in Lake Michigan water levels. He believes this resulted because the slopes of the till bluffs may stand vertically following wave attack, "but eventually, [even if lake levels drop and there is no direct wave impact] surface runoff, seepage, and freezing and thawing, combined with the load of the material above, may cause the bluff to disintegrate" (p.86). This may explain at least some of the apparent contradiction between Davis, et al. and Seibel.

The stratigraphic sequence of material within the bluff may have a considerable influence on the characteristics of recession and erosion (Pincus, 1962; Edil and Vallejo, 1977; Mickelson, et al., 1977), especially when ground water percolation is present. "Slope failure caused primarily by ground water seepage and [porewater] pressure is a common occurrence in coastal bluffs along the Great Lakes" (Gray, 1975, p. 12). The problem is often compounded where the arrangement of bluff material includes alternating layers of pervious and relatively impervious unconsolidated deposits. Lapham (1847), Whitney (1936), Murphy and Keim (1968), Hadley (1974; 1976), and Lee (1975) credited ground water percolation as a prime cause for bluff recession along several Wisconsin lakeshore segments. Surface runoff can also contribute significantly to bluff slope retreat and erosion (Chieruzzi and Baker, 1958; Pincus, 1962). Ball (1920) disclosed that drainage from tiled fields facilitated slumping of a Wisconsin bluff whereas Buckler (1973) reported that channelization of runoff initiated severe gullying into the bluff slope.

Recently attention has focused on the importance of vegetation on the shorezone bluff slopes (Hall and Ludwig, 1976; Acres Consulting Services, 1976; Dai, Hill, and Smith, 1977; Great Lakes Basin Commission and U.S.D.A. Soil Conservation Service, 1977; and Illinois Coastal Zone Management Program, 1978). It is recognized that vegetation is not an effective measure against wave forces (Haras, 1977) but its influence on terrestrial slope processes can be quite significant.

> Vegetation helps to control terrestrial slope erosion and mass-wasting by root reinforcement of soil, by restraint and "filtering" of soil particles, by restraint of soil masses on slopes by "soil-arching" effects, by interception of precipitation, by retardation of runoff and maintenance of infiltration capacity and by depletion of soilwater (Gray, 1977, p. 5).

Furthermore, it is vegetation that largely allows lakeshore dunes to form and be maintained; it traps and holds sand blown up from the beach, especially during low water periods. Foredunes built up during these times may protect higher inland bluffs from wave erosion when the lake again rises. The U.S. Army Coastal Engineering Research Center (Knutson, 1977) has recently begun dune-building experiments using American beachgrass and prairie sand reed along Lake Michigan at Ludington State Park, Michigan.

Zumberge and Wilson (1953), O'Hara and Ayers (1972), Davis (1973), and Marsh (1977) have discussed another natural protective barrier. They indicate that erosion could be much more severe if it were not for the formation along the shoreline of icefoots and ice ridges which shield the beach and bluff from frequent and potentially damaging storm waves each winter.

Shorezone bluff geometry is dynamic; it changes over time as a consequence of toe erosion and bluff face degradation (Edil and

Vallejo, 1977; Vallejo, 1977). In order to form engineering and management solutions to problems created by retreating bluffs the mechanics of slope evolution, the mode of slope failure, and the inherent stability or instability of the slope have been studied (Mickelson, et al., 1977; Edil and Vallejo, 1977; Vallejo, 1977).

Goldthwait (1907) recognized that the till bluffs along the southern part of the shoreline in Kewaunee, Wisconsin, had been rapidly retreating until the town's long piers were constructed; subsequently a beach formed at the base of the bluff due to littoral drift accumulation caused by entrapment by the piers. It is believed by many, however, that similar and so-called protective shorezone structures may actually increase erosion rates along some lakeshore segments because they trap littoral drift and thus limit sand movement and downdrift beach formation (Ball, 1938). McGee (League of Women Voters, 1974) and Larsen (1972) have suggested that a large percentage of the present acceleration in shoreland recession along Lake Michigan is directly related to an increase in the number of shoreline structures. Part of the 1968 Federal River and Harbor Act mandated that the U.S. Army Corps of Engineers "investigate, study, and construct projects for the prevention or mitigation of shore damages attributable to Federal navigation works" (Great Lakes Basin Commission, 1975, p. 54; for a description of the various projects see U.S. Army Corps of Engineers, 1977, pp. 64-69). Subsequent studies have indicated that for 27 areas of the Great Lakes shoreline Federal navigation works are wholly or partially responsible for shorezone erosion in at least 17 cases (Omohundro, 1973). For example, the jetties at South Haven, Michigan, were determined to cause 81% of the total erosion in the nearby shore damage area (U.S. Army Corps of Engineers, 1974) whereas only 30% of the total erosion at St. Joseph, Michigan, was thought due to the harbor structures (U.S. Army Corps of Engineers, 1973b; also see Linney, 1976). A study by Gove Engineers (1970) had earlier concluded that the St. Joseph jetties created conditions under which shoreland erosion was accelerated.

Herbert (1974), through a model analysis of the St. Joseph shorezone, examined the combined environmental, engineering, and legal approach in providing long-term solutions to erosion problems along developed shores. Although largely inconclusive, Frankovic (1975) attempted in a M.S. thesis to construct a model to duplicate erosional events along a portion of the Milwaukee County, Wisconsin, shoreline and to test the effectiveness of various shore protection structures.

Numerous governmental and other publications directed at informing the public about shorezone erosion conditions and processes and/or providing technical assistance relating to erosion protection devices and shorezone management alternatives along Lake Michigan and the Great Lakes are available.[12] Bibliographies have been published dealing, entirely or in part, with shoreline recession and conditions along Lake Michigan (Brater, 1950b; Mitchell, 1968; Water Resources Scientific Information Center, 1972; Lasca, 1975; Stark, 1975).

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[12] Brater, Billings, and Granger, 1952; Brater, 1954, 1975; Michigan Water Resources Commission, 1970, 1972a, 1972b, 1972c; U.S. Army Corps of Engineers, 1971a, 1971b, 1971c, 1972, 1973a, 1973b, 1975c, 1976; Verspoor, 1972; Buddecke, 1973; Michigan Department of Natural Resources, 1973; Omohundro, 1973; Wisconsin Sea Grant Program, 1973, n.d.; Brater, Armstrong, and McGill, 1974, 1975; League of Women Voters, 1974; Marks and Clinton, 1974; Uyl, 1974; Great Lakes Basin Commission, 1975a, 1975b, 1977; Napolii, 1975; Hadley, 1976; Hartford and Tanner, 1976; Brater, Armstrong, McGill, and Hyma, 1977; Hanson, Perry, and Wallace, 1977; Marks, 1977; Mickelson, et al., 1977; Wisconsin Department of Natural Resources, 1977; Lake Michigan Federation, 1978; Michigan Division of Land Resource Programs, 1979a, 1979b.

Workshops and conferences have been held concerning shore erosion and planning (Lake Michigan Federation, 1973; Michigan Legislature, 1974; Great Lakes Basin Commission, 1975b; Great Lakes Basin Commission and U.S.D.A. Soil Conservation Service, 1977; Rukavina, 1978) and several programs have been conducted to study or observe the problems in the field (Upchurch, 1973; Collinson, Lineback, DuMontelle, and Brown, 1974; Gorder, 1975; Geological Society of America, 1976; among others).

Collectively these numerous references indicate that the Lake Michigan shorezone is a dynamic environment that is not completely understood. Studies show that bluffs are receding at rates that are not uniform along the shoreland nor are they necessarily similar during two different time periods at a given site. Nearshore topography, storms, ground water seepage, shorezone structures, shoreline orientation, slope failures, beach conditions, and/or bluff composition may be important factors affecting lakeshore bluff recession. Studies contain conflicting data and conclusions regarding these relationships, however.

Little research has been conducted comparing the conditions between the Michigan and Wisconsin shorezones. It is possible that apparent relationships existing along one lakeshore interact in a somewhat different fashion elsewhere. Information of this nature may be especially useful in making estimates of future bluff crest positions and decisions regarding shorezone management.

Justification and Applicability

Frequently shorezone occupants have found that protective devices are not effective in controlling the natural forces that erode the shoreline bluffs and threaten or destroy their property (Mitchell, 1974). Some have suggested that the level of Lake Michigan be regulated during periods of high water, thereby minimizing potential shorezone erosion. Unfortunately, this proposal leads to conflict with other lake users; for instance, commercial navigation and power generation concerns benefit from high lake levels. In any case, the International Joint Commission (International Great Lakes Levels Board, 1973, p. 4) has concluded after a 10-year study that

> regulation of Lakes Michigan-Huron by construction of control works and dredging of channels at their outlet, combined with the regulation of Lakes Superior and Ontario, would not provide benefits commensurate with costs

and therefore would not be a viable shorezone management alternative.

Many are now recognizing the need to restrict further structural encroachment upon the slopes and tops of those bluffs vulnerable to rapid wave erosion. Indeed, the IJC (International Great Lakes Levels Board, 1973, p. 5) concludes that "the most promising measure for minimizing damages to shore property interests are strict land use zoning and structural setback requirements."

Hadley (1976, p. 30) focuses on a major problem concerning lakeshore zoning, however, when he states

> that there is not at present time a sufficient body of factual information on the geologic, hydrologic, and geotechnical or engineering conditions along the lake to allow rational decisions as to the stringency of zoning necessary along the various segments of the coast.

In a comprehensive study assessing Great Lakes shoreland management problems the Great Lakes Basin Commission (1975a, p. 12) concluded that "because of the dearth of criteria for the establishment of building setback and height controls, effective controls are generally absent in many shoreline areas of the Great Lakes." Furthermore, the commission strongly urged the establishment of a systematic and comprehensive erosion rate study that would compile historic erosion rates for the entire Great Lakes shoreland. Buddecke (1974, p. 5) had previously reached a similar opinion at a Great Lakes Recession Workshop where he emphasized:

> recession rate information is urgently needed to support Coastal Zone Management activities, the Land Drainage Reference Study of the IJC, the Permit Program of the Corps of Engineers, and the Flood Insurance Program administered by the Department of Housing and Urban Development.

A primary goal of this study is to determine and assess historic and recent rates of bluff crest recession at a large number of sites along the erosion prone shorelands of Wisconsin and Michigan in order to provide reliable data useful in formulating lakeshore management alternatives and zoning regulations. By comparing the east and the west shorezones of Lake Michigan this research also attempts to address such questions as: Is one side of the lake eroding more rapidly than the other side? And are conditions similar or is each shorezone characterized by unique problems or processes?

Surely most lakeshore bluffs will continue to erode in the future, although the rate at which they will recede is open to question. Continued bluff recession may have adverse effects, physically, psychologically, and financially, on shorezone communities. For example, wave erosion obliterated the initial 1880's lakefront settlement of

Two Creeks, Wisconsin (Wojta, 1945). Road segments in several counties (for instance, Kenosha and Manitowoc Counties, Wisconsin, Berrien County, Michigan, and Porter County, Indiana) have been destroyed and/or relocated due to appreciable bluff recession. Hundred of houses and related structures have likewise been affected. Some shorezone reaches are now recreationally unusable, even during low water stages, because hazardous items such as broken concrete slabs, auto and truck bodies, and tires have been dumped on the bluff slopes and beaches in an attempt to prevent bluff recession. Millions of dollars have been spent on structures to protect railroad and highway rights-of-way in St. Joseph, Michigan, and are being expended in an effort to mitigate shorezone erosional damage caused largely by Federal harbor jetties at numerous localities along Lake Michigan. In Wisconsin alone, losses in excess of 30 million dollars have occurred during the present high lake period due primarily to wave erosion on the bluff (Seibel, Armstrong, and Alexander, 1976). With intensifying occupation and generally rising land values along the lakeshore future damages from bluff recession could conceivably reach into the hundreds of millions of dollars.

Chapter 2

SHOREZONE CHARACTERISTICS AND CONDITIONS FAVORING SHORELAND EROSION

Introduction

Lake Michigan is situated within a bedrock lowland mantled in most places by unconsolidated Quaternary sediments. Extending 307 miles in a north-south direction and 118 miles at its widest breadth, its 1,362 miles of shoreline encompasses a water surface area of 22,300 square miles. The lake, located in the westerly wind belt, experiences periodic storms producing wave erosion that modifies the shorezone topography. Annual and seasonal variations in precipitation and evaporation resulting from shifts in cyclonic storm paths result in lake level changes; and these lead to changes in shoreline positions and beach widths. Lakeshore erosion and bluff recession appear to be primarily dependent upon the interaction of onshore storm waves, lake level, shorezone physiography, longshore currents, and nearshore hydrographic conditions.

Shorezone Terminology

Shorezone terms used in this study are defined in Appendix A and shorezone features are illustrated in Figure 2.

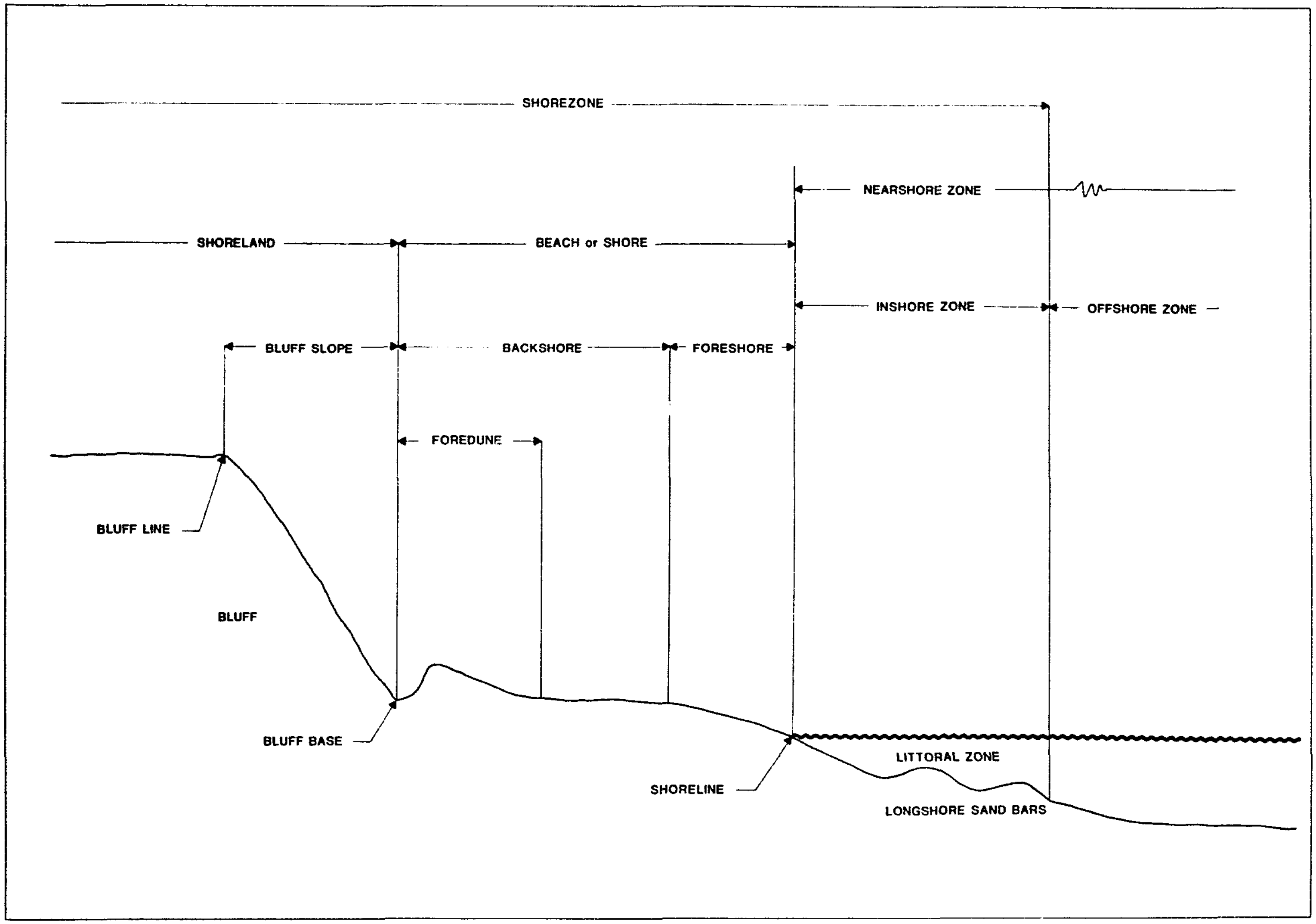

Figure 2. Shorezone features referred to in this study.

Shorezone Physiography

Shoreland Bluffs

The shoreland bluffs considered in this study vary from low to high banks of unconsolidated Quaternary sediments. These largely consist of glacial drift,[1] dune sand, and post-glacial lacustrine and shore material[2] and have been described by numerous investigators.[3] Although the bluffs may be composed of a single sediment exposures commonly reveal two or more stratigraphic components; for example, relatively impermeable zones of till and/or lacustrine clays are often found interbedded with permeable layers of glacio-fluvial material. And bluffs in sand dunes may be forming in relict features associated with ancestral proglacial lakes of higher elevation or in modern dunes that have formed quite recently along the lake margin.

The Wisconsin and Michigan shorelands are similar because both are products of Pleistocene and Recent processes but significant differences do exist. Bluffs in Wisconsin tend to be lower and, as a whole, are composed of a larger percentage of clay-rich material (Seibel, Armstrong, and Alexander, 1976; Krumbein, 1950). Sand dunes

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[1] Drift is defined as "any rock material, such as boulders, till, gravel, sand, or clay, transported by a glacier and deposited by or from the ice or by or in water derived from the melting of the ice" (American Geological Institute, 1974, p. 146).

[2] At numerous places, however, the natural bluff face is presently covered by artificial fill and/or is fronted by a protective structure. In a few places dolomite bedrock outcrops in the beach zone in Manitowoc, Sheboygan, Milwaukee, and Racine Counties, Wisconsin (Mickelson, et al., 1977, p. 41).

[3] Scott, 1942, n.d.; Martin, 1955; Powers, 1958; Humphrys, Horner, and Rogers, 1958; Striegl, 1958; Gifford and Humphrys, 1966; Farrand, 1969; Hands, 1970; Gorder, 1975; Edil, Mickelson, and Acomb, 1977; Vallejo, 1977; Acomb, et al., 1977; and others.

form a very limited portion of the Wisconsin shoreland studied and these are largely confined to two small tracts near Two Rivers and Sheboygan and both generally display less than 15 feet in local relief. Small subdued dunes, generally no more than several feet in height, also exist along a few other backshore segments of quite limited extent. In contrast, dunal topography occupies a number of extensive areas along the Michigan shorezone. Here relative relief may exceed 150 feet and the dunal tracts may be more than a mile in width and extend for miles along the shore. Furthermore, a variety of eolian forms possibly of different ages may overlie or juxtapose non-dune formations. Separating the dunal segments are bluffs constructed largely of drift that may approach heights of 300 feet in the northern part of the study area.

Beaches

Lake Michigan beaches reflect lakeshore physiography, wave regimes, lake levels, littoral currents, and availability of sediments. During low water levels beaches may widen considerably (Davis, Seibel, and Fox, 1973; Bascom, 1964) and low-relief sand dunes may form in the backshore areas. In contrast, at times of high lake elevations, and especially during intense wave activity, beaches tend to be much narrower or may even be temporarily eliminated (Davis, Seibel, and Fox, 1973; Bascom, 1964). But differences exist between the Michigan and Wisconsin lakeshores; on the average Michigan beaches are wider than those on the west side of the lake (Krumbein, 1950). Along the Wisconsin lakeshore beach widths seldom exceed 100 feet (Krumbein, 1950); this figure is exceeded at many places along the eastern shore (Hulsey, 1962). Beach sediments range from sand to boulders with sand beaches predominating in the Michigan study area (Hulsey, 1962). Sand beaches are also most common in Wisconsin but here coarser particles, although unevenly distributed, tend to comprise a higher proportion of beach segments.

Longshore Sand Bars

Longshore sand bars occupy the nearshore zone along much of Lake Michigan. They are most prevalent in the eastern lakeshore (Hands, 1976) but their extent appears to be limited along the Wisconsin reach (Hands, 1970), probably because less sand is available (Saylor and Hands, 1970).[4] Numerous investigators have described these features (Evans, 1940; Davis and McGeary, 1965; Hawley and Judge, 1969; Saylor and Hands, 1970; Davis and Fox, 1972a; Hands, 1976; among others). Often continuous for miles, longshore bars parallel the strand line and generally number two or three but may reach four or five. An ephemeral bar may form closest to shore and merge into the beach face instead of conforming to the shoreline trend. The sand bars seem relatively unaffected by severe storms (Davis and McGeary, 1965; Davis and Fox, 1971) but their crests appear to change position, especially with variations in lake level (Evans, 1940; Hawley and Judge, 1969; Saylor and Hands, 1970; Hands, 1976). Apparently these features are of considerable importance because wave energy is diminished as waves steepen and break over the bars. According to Davis et al. (1973) variations in bar characteristics and spacing probably account for much of the differences in local rates of bluff recession.

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[4] Davis and Fox (1972a) indicate that abundant sand size sediments and a gradually sloping nearshore bottom are prime prerequisites for nearshore sand bars. The Wisconsin bluffs, especially in the southeast, are largely composed of fine-grained lacustrine sediments and silty and clayey till. Consequently, only a relatively small amount of the material eroded from the shorezone bluffs is sand which is able to be retained in the beach and nearshore zone (Hadley, 1976).

Shorezone Ice

The Lake Michigan shore normally becomes ice bound in December with the condition lasting until late March or April. Zumberge and Wilson (1953), O'Hara and Ayers (1972), Davis (1973a), Evenson (1973), Seibel, Carlson, and Maresca (1976), and Marsh (1977) have investigated this phenomenon. With the onset of winter temperatures several conspicuous ice ridges typically form parallel to the strand line in the nearshore zone. These are separated by wide areas of low, rough ice and the whole complex becomes firmly attached to the shore with portions resting on the lake bottom (Marsh, 1977). During this time the beach zone changes from a dynamic to a nearly quiescent environment (Davis, 1973a) because waves are unable to reach the beach and shoreland bluff. The protection the ice affords the bluff against wave erosion is important because it is during winter when the passage of cyclonic storms (with their associated waves) is most frequent. Furthermore, it is along just those lakeshore reaches with the greatest exposure to storm waves, and where nearshore water depths increase only gradually, where the largest ice complexes tend to develop (Marsh, 1977).

Lake Level Variations

Lake Michigan's elevation[5] fluctuates in accordance with at least three distinct time sequences of different magnitudes. Short-term changes are imposed on seasonal fluctuations which in turn are superimposed on long-term oscillations (International Great Lakes Levels Board, 1973b; Buckler, 1972b; among others). Short-term changes lasting from a few hours to several days are caused by meteorological disturbances. For example, winds and differences in barometric pressure can cause temporary imbalances in the water's altitude at different locations although no change in lake volume is involved. In some places the water elevation can rise or fall more than three feet because of these conditions.

During each year the lake surface fluctuates an average of 1.1 feet in a predictable seasonal cycle (International Great Lakes Levels Board, 1973b). Runoff from spring snowmelt and rainfall causes the lake to gradually rise, reaching its yearly peak in July or August. Subsequently, lake levels tend to decrease because of increasing evaporation and generally lower rainfall in late summer and autumn.

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[5] Hydrologically, Lakes Michigan and Huron are considered to be a single unit because of their wide and deep connection at the Straits of Mackinac; they have no measurable difference in surface elevation. At a given time their water level depends primarily on whether the lakes are receiving more or less water than they are losing. The water supply consists of precipitation on the lakes' surfaces, runoff from their drainage areas, inflow from other lakes, diversion of water into their basins, and ground water inflow. Water is removed from the lakes by evaporation, diversion to another drainage basin, outflow from the lakes through their natural outlets, and ground water seepage. Approximately 70% of the contemporary variation in the Lake Michigan-Huron level is related to basin precipitation (Muller, et al., 1965; Brunk, 1960). "Because of the size of the Great Lakes and the limited discharge of their outflow rivers, extreme high and low levels and flows persist for considerable time after factors which caused them have changed" (U.S. Army Corps of Engineers, 1972, p. 2).

The lake generally reaches its lowest level between January and March after freezing temperatures severely retard inflow of basin runoff.

The 117-year hydrographic record, however, reveals significant differences in yearly and seasonal mean levels (Figure 3). Generally, a few consecutive years of below average lake levels are followed by a number of years with above average elevations; but both the length of these periods and magnitude of change are variable and unpredictable. Differences in annual mean lake elevations result primarily from persistence in below or above average basin precipitation for several years (Muller, et al., 1965; Brunk, 1960). These variations in annual precipitation result from changes in mid-to-upper tropospheric air flow currents that support and guide cyclonic systems across North America (Buckler, 1972b).

The average annual level of the lake surface has varied as much as 5.62 feet[6] since 1860; if monthly average levels are considered, Lake Michigan's maximum variation is 6.59 feet during this period.[7] Since the all-time recorded low in 1964, a tendency toward above average annual precipitation resulted in a rise of the lake; 10 years later, in July, 1974, the water reached an elevation of 581.05 feet, 2.39 feet above its long-term (1900-1977) July average. Although now below its 1974 level the lake remains above its long-term average. Because of

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[6] Average 1964 level: 575.66 feet; average 1886 level: 581.28 feet. Freeman (1926) and Day (1926) cite the Board of Engineers on Deep Waterways report (Secretary of War, 1900) referring to an even earlier authenticated higher level of 582.56 feet (this figure has been corrected to the 1955 IGLD) in 1838.

[7] March, 1964 level: 575.35 feet; June, 1886 level: 581.94 feet.

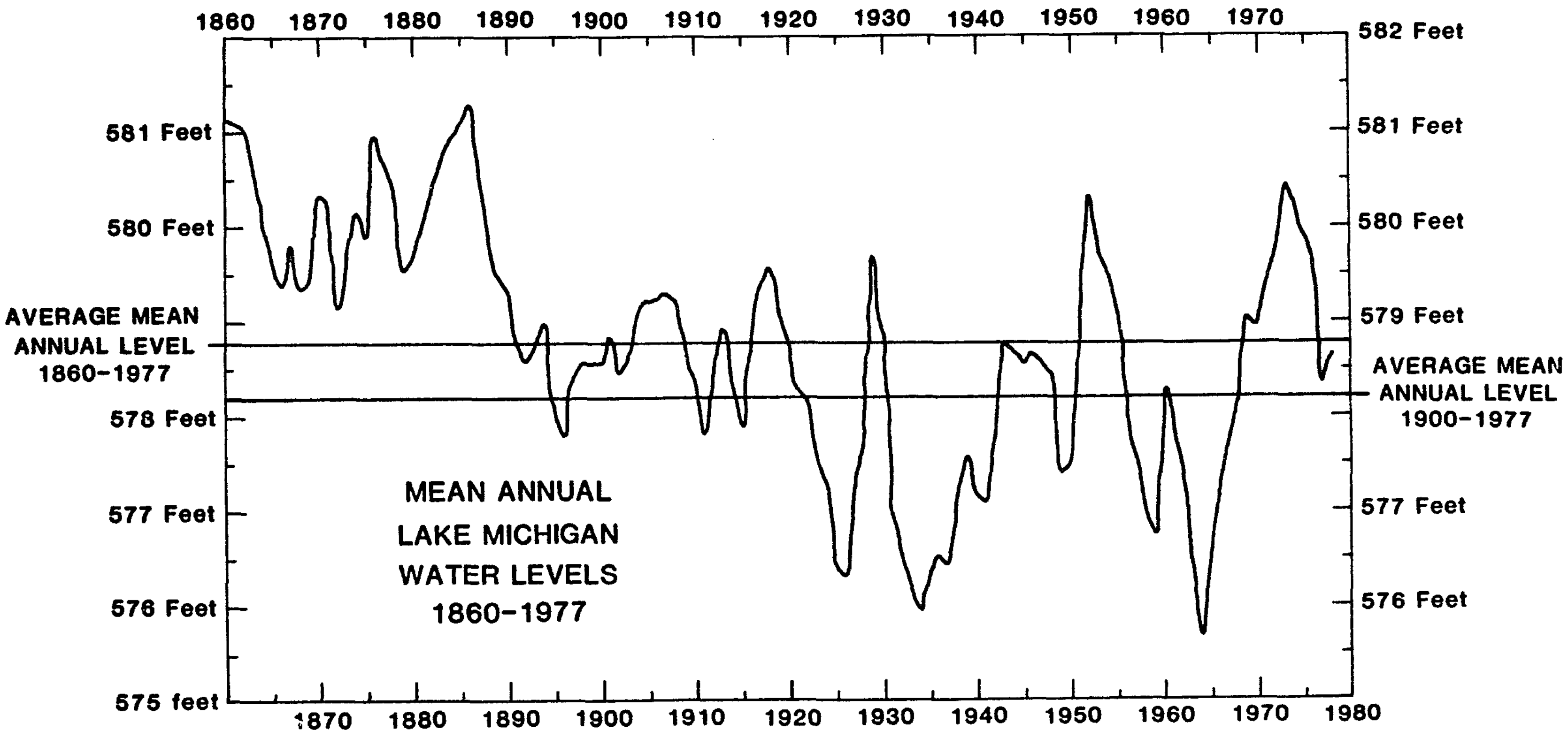

Figure 3. Long-term average annual water levels of Lake Michigan.

these levels, combined with gentle nearshore slopes,[8] beaches have tended to remain relatively narrow for the past decade and considerably diminished from the wider widths that existed during the early 1960's.

Winds, Waves, and Currents

Wind-generated waves initiate most of the erosion along the Lake Michigan shorezone. Increase in wave size, and therefore wave energy and potential erosional ability, occurs with increase in wind velocity, wind duration (from a constant direction) and fetch.[9] Wave development on the lake is probably most restricted by fetch but the impact of this factor varies significantly because of its north-south orientation. Due to Lake Michigan's large size and the magnitude of atmospheric disturbances waves may be produced that are comparable in size with those observed on many seacoasts (Hough, 1958). There are indications, though, that a greater amount of deep water storm wave energy is transmitted toward the Michigan shore than toward the Wisconsin lakeside (Saville, 1953; Davis and Fox, 1974).

Waves usually approach the shore at acute angles and as they break they produce longshore currents that move parallel to the shoreline.

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[8] Gentle nearshore slopes permit substantial changes in beach width with relatively small changes in lake altitude. Wide beaches characterize periods of low lake elevation and narrow beaches typify times of relatively high water levels.

[9] Nevertheless, waves can only increase in size to a maximum physical limit. Wind velocity, wind duration or fetch can independently set a wave size limit (King, 1972). For example,

> ...however long the wind blew at great speed it could not generate large waves if the fetch were limited. This limit could be imposed either by the meteorological situation, which determines the distance over which a wind is blowing in a constant direction, or by the configuration of the water body, which in some areas determines the fetch available for wave generation (King, 1972, p. 46).

This action results in the redistribution and subsequent deposition of sediments introduced into the nearshore primarily by waves eroding the shoreland bluffs. Beach maintenance and accretion is largely dependent on sand supplied by longshore currents and blockage updrift by structures such as groins and harbor jetties tend to significantly limit natural sand replenishment. Along both the east and west margins of Lake Michigan's southern basin net longshore drift is southerly. But along the northern portion drift is predominantly northward although reversals in direction occur (Hands, 1970; Seibel, Armstrong, and Alexander, 1976).

Storms

Strong sustained winds necessary for development of large waves along the Lake Michigan shore are associated with cyclonic disturbances moving across the Great Lakes region. Although occurring throughout the year these storms are most frequent and intense between late fall and early spring when the principal storm tracks of the westerlies are in their intermediate and southerly positions. The Great Lakes is a preferred region for cyclonic activity during the cold season (Peterssen, 1950) where between November and April two primary storm tracks, one originating over the southwestern United States and the other over western Canada and the northern Rocky Mountain region,[10] tend to converge (Klein, 1957).

Seibel (1972) demonstrated that the rate of bluff recession is not related to the total number of storms which pass across the Great Lakes but rather to the larger storms of the year. For the period

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[10] These will be referred to as Alberta-type lows.

October through February, 1955 to 1976, Rosen (1978; Harman, Rosen, and Corcoran, 1980) determined that cyclonic activity was greater in December and January but the highest total of "deep" cyclones occurred in November. Also, cyclones originating over the southwestern United States were the more intense storms, and of these, the highest percentage took place in November.[11] Furthermore, Rosen concluded that for cyclones to become extremely intense over the Great Lakes they must meet certain criteria, namely a sharp air mass temperature contrast, strong support aloft, and moist air input from the Gulf of Mexico (provided by origination in the southwestern United States). The absence of moist Gulf air probably accounts for the fact that although Alberta-type lows are the most frequent in the Lake Michigan area in all seasons (Cooperman, et al., 1959; Jay Harman, personal communication), the majority are relatively weak with winds generally insufficient to generate destructive wave action against the shorezone bluffs.

Commonly it is the deep low pressure system moving slowly across the Great Lakes district from the southwest that leads to accelerated wave-cut bluff erosion along the Lake Michigan shorezone. Although the cyclone may pass through the area in a northeasterly direction the winds and wave regimes it generates over and along the margins of the lake will vary depending on the position of the storm center; consequently, not all parts of the lakeshore come under especially severe wave attack at any one time. For example, easterly to northeasterly winds are typically associated with the leading edge of these disturbances. If of gale force, they may generate waves that

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[11] That does not mean that severe disturbances cannot take place during other months of the year or originate from the northwest.

are particularly damaging along the western and southern shorezones. Because of the potentially long fetch involved the largest waves to affect Wisconsin are usually generated by northeasterly storm winds (Hadley, 1976; Mickelson, et al., 1977). Southerly and southwesterly winds are characteristic when the center is positioned over the lake.[12] At this time the eastern and especially the northeastern and northern shorezones are particularly vulnerable to wave erosion. The trailing edge of the storm cell commonly produces the strongest winds--from the north to northwest (Jay Harman, personal communication); most of the severe wave erosion along southeastern Lake Michigan is attributed to these winds[13] (Davis, Fox, Hayes, and Boothroyd, 1972).

Summary

The primary force causing bluff erosion and recession along Lake Michigan is wave activity during high intensity storms when lake levels are high. These disturbances are most frequent between October and April and tend to be most severe in November. During times of low water most of the energy of these waves are released on and absorbed by longshore sand bars (if present) and beaches fronting the lakeshore bluffs. While some erosion may take place during low and intermediate lake levels, it is accelerated when storm waves are superimposed on high lake levels. During these periods the beaches are narrower or submerged, allowing waves to break close to or directly against the highly erodable

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[12] This condition also commonly exists on the leading edge of an Alberta-type low moving across the western Great Lakes.

[13] North to west winds are also typically associated with the trailing edge of Alberta-type lows as they pass through the western Great Lakes district.

unconsolidated bluffs. Under such conditions their bases may be rapidly undercut, leading to instability and eventual failure of the slopes and recession of the bluff crests. Regardless of Lake Michigan's level the high frequency of large storms during the fall season (and to a lesser extent the spring season) commonly does not allow the beach to fully recover during the low energy conditions between storms (Seibel, Armstrong, and Alexander, 1976). Consequently, erosion, or at least the potential for erosion, may become progressively more acute as the storm season advances.

Bluff erosion, however, is generally minimal during the winter and summer seasons. The build-up of shorezone ice affords a timely protective barrier against winter storm waves. And because summer is typically a low energy period beaches at this time characteristically reach their widest annual widths. Large summer storms are not common but when they do occur, and even though waves are superimposed upon the highest annual water level, the beaches are generally sufficient to dissipate the incoming wave energy without serious damage to the bluff. Following the disturbance there is usually enough time before another summer storm occurs for the beach to recover fully.

Chapter 3

SITE CHARACTERISTICS, RATES AND SPATIAL VARIATIONS OF LONG-TERM BLUFF RECESSION, AND RELATIONSHIP OF SELECTED VARIABLES TO BLUFF RETREAT

Introduction

Bluff Crest Recession and Bluff Erosion

Bluff crest recession is "essentially a geometric concept, involving the landward displacement of...bluff lines" and bluff erosion "is a mass concept involving the net removal of bluff material" (Pincus, 1962, p. 124). Although they may take place simultaneously, one can occur without the other.[1] The time lag between initiation of basal erosion and crest recession may range from seconds to several hours, months, or years and, for some high bluffs, perhaps even more than one episode of high lake levels. Bluff crest recession is the primary interest in this study because it most directly affects development of the shoreland surface.

Long-Term and Short-Term Bluff Recession

In this study long-term bluff line recession represents losses incurred over an interval of at least 120 years whereas short-term retreat generally represents a period of two decades or less. Recession rates at a given location may vary during different length periods but

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[1] For example, storm waves may remove the base of a cohesive till bluff slope without initiating a simultaneous movement of the bluff crest. Or, irrespective of recent storm waves, the crest may recede due to failure and slumping of the upper slope; the slope profile would change but there would be little net loss of bluff material.

these changing conditions may be obscured by long-term recession values. Consequently, estimates or projections based on these long-term values may not be applicable for shorter time spans, especially if these periods coincide with either a low or high lake stage. For example, some of the bluff sites in this investigation have undergone considerable losses during the last 12 years yet their long-term average annual recession rates are relatively low, and at some sand dune locations net accretion has even occurred. Likewise, it may be misleading to predict long-term shorezone evolution solely on changes taking place over only several years or a single decade.

Spacing and Point Nature of the Sites

Long-term bluff recession rates are based on data from 118 sites that are, with two exceptions, a minimum of one mile apart, but this distance is commonly greater and spacing tends to be uneven. Being shorter in length but entailing more sites (62) the Wisconsin lakeshore is more uniformly sampled than the Michigan shorezone where sites (56) tend to be more widely spaced (Figure 4). Theoretically each site is represented by a single point along the bluff. Because of the wide spatial and temporal variation in bluff recession the position of the bluff line and its rate of retreat may not necessarily be representative of nearby bluff segments, especially on a short-term basis. Nevertheless, collection of data and identification of long-term patterns and relationships concerning Lake Michigan bluff recession and shorezone evolution is possible because of the large number and variety of sites investigated. Furthermore, although conclusions are based on measured data from 118 section line sites, field and aerial photographic observations at numerous other locations lend support to the premises presented.

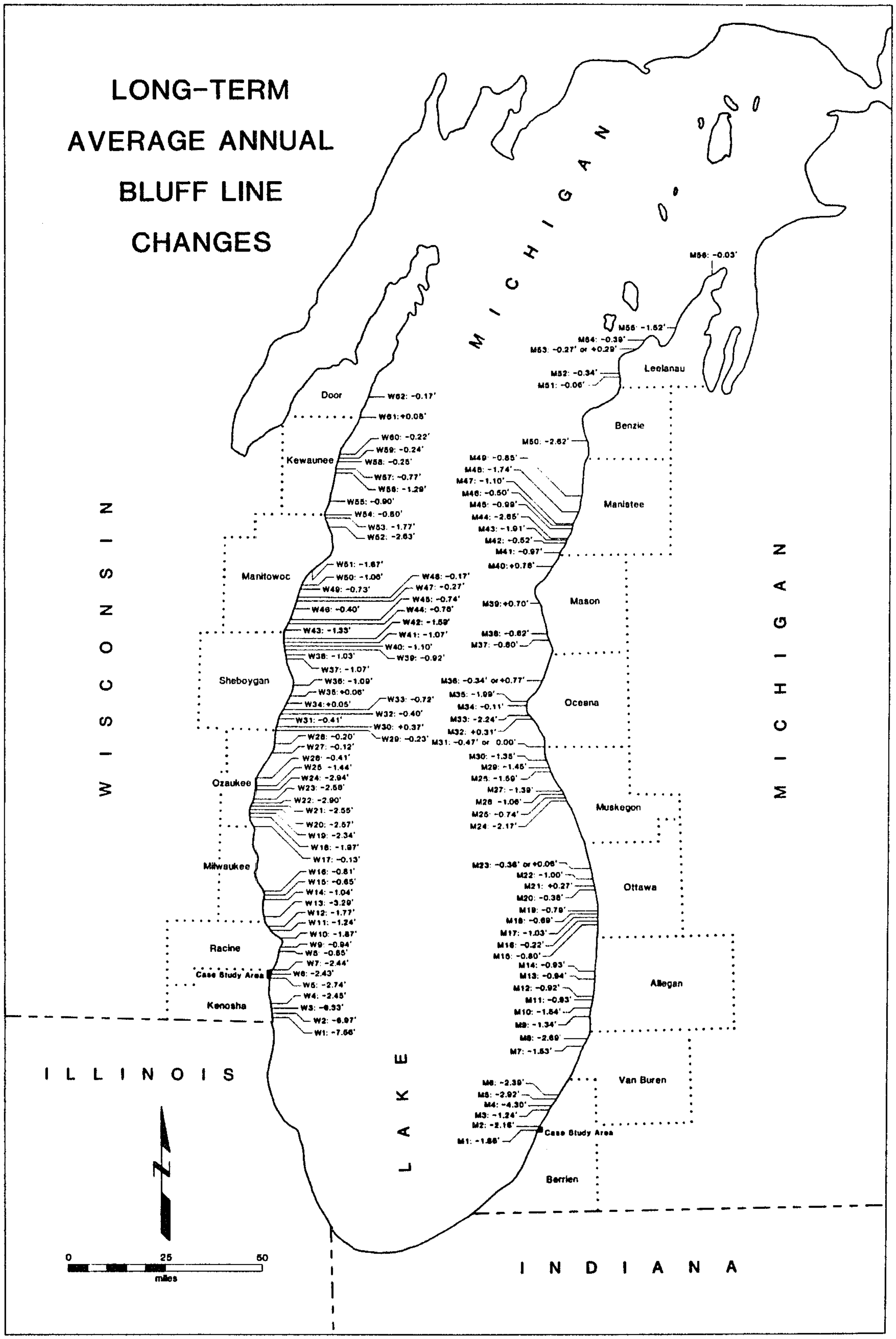

Figure 4. Site locations and their long-term average annual bluff line changes.

Site Characteristics

The range in characteristics of the 118 sites reflects the variation in Lake Michigan shorezone physiography (site descriptions are summarized in Appendix B). Sixty percent of the Michigan sites consist of bluffs composed entirely of dune sand or of dune sand overlying other sediments. These conditions exist at only 16% of the Wisconsin sites and most of these are concentrated in southern Sheboygan County. At the study locations dune sand reaches thicknesses as great as 50 feet in Michigan but never more than five feet in Wisconsin.

A greater proportion of the Wisconsin sites include bluffs of various non-eolian Quaternary material. Both permeable and relatively impermeable sediment zones occur in 36 of the 62 Wisconsin bluffs but are found at only 19 of the 56 sites in Michigan. Ground water discharge is especially common where permeable strata overlie relatively impermeable material. This condition has important geomorphic implications because ground water seepage may contribute significantly to bluff slope failure.

In Wisconsin bluff heights at the sites vary from one to 120 feet, with bluffs at 16 localities under 10 feet and six at 100 feet or greater. Low lacustrine terraces adjacent to the shoreline account for these numerous low bluff locations. Bluff sites in Michigan range from six to 310 feet in height, with only five under 10 feet but eight over 100 feet.

During the present high lake stage (Figure 3) appreciable erosion of the bluff base has occurred at 57 of the 62 Wisconsin sites and at 53 of the 56 Michigan locations. In contrast, at 12 of the section lines in Wisconsin and at 16 in Michigan bluff crest retreat had been negligible or non-existent during this period, even though many have undergone considerable recession during the last 120 years or more.

Rates of Long-Term Bluff Line Change[2]

Data from at least 106 of the 118 section line sites in both Wisconsin and Michigan show long-term bluff crest recession. For the period studied the average annual retreat for these 106 locations is 1.43 feet (0.436 m) but net losses range from as little as 3.64 feet (1.11 m; site M56) to as much as 1066.32 feet (325 m; site W1). Eight other sites, however, show long-term accretion, varying from a net gain of 6.45 feet (1.97 m; site W34) to 104.25 feet (31.78 m; site M40). Table 1 summarizes the variation in average annual bluff crest changes and Tables C1 and C2 (Appendix C) show the site locations and corresponding recession and accretion data.

Spatial Variation in Bluff Line Changes

Individual sites and extended reaches within both the Wisconsin and Michigan study areas display a wide variability in bluff line changes (Figure 4 and Tables 1, C1, and C2). But contrary to expectation overall average annual long-term bluff crest recession for the two lakeshores is similar. Analysis of data from the different shorelines using Student's t tests indicate statistically no significant difference (at the .05 significance level) in the two sample populations (Table 2).

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[2] At four Michigan sand dune sites (M23, M31, M36, and M53) two distinct bluff crests are recognized. The lakeward crest is a bluff line of a lower-relief dune terrace which fronts the more landward crest of a somewhat higher-relief dune feature. At these locations it was unclear as to which crest the resurvey should be carried to in order to compare it with the original GLO measurements. Therefore, values are reported based on both possible bluff line positions. In three of the four cases measurements to either crest indicated only small net changes in bluff line position relative to the GLO survey. The recession or accretion rates determined for these four sites are not included in any of the quantitative analysis performed in this study. In no way does this exclusion affect the conclusions reached and, in fact, their inclusion would only increase support for the findings reported.

Table 1. Variation in long-term average annual rates of bluff line change at the Wisconsin and Michigan study sites.[a]

	Wisconsin	Michigan	Total
	Number of Sites		
Bluff Sites Which Experienced Recession:			
Average Annual Recession			
less than 0.50 ft.	14	8	22
0.51 ft. to 1.00 ft.	12	15	27
1.01 ft. to 1.50 ft.	11	8	19
1.51 ft. to 2.00 ft.	6	8	14
2.01 ft. to 2.50 ft.	4	4	8
2.51 ft. to 3.00 ft.	7	4	11
3.01 ft to 3.50 ft.	1	0	1
3.51 ft. to 4.00 ft.	0	0	0
greater than 4.01 ft.	3	1	4
Bluff Sites Which Experienced Accretion:			
Average Annual Accretion			
less than 0.20 ft.	3	0	3
0.21 ft. to 0.40 ft.	1	2	3
0.41 ft. to 0.60 ft.	0	0	0
0.61 ft. to 0.80 ft.	0	2	2
Average Annual Rate of Long-Term Bluff Recession	1.43 ft. (0.436 m)	1.16 ft. (0.354 m)	1.31 ft. (0.399 m)
Normalized[b] Average Annual Rate of Long-Term Bluff Recession	1.15 ft. (0.351 m)	1.10 ft. (0.335 m)	1.13 ft. (0.344 m)

[a] The double-crested Michigan dune sites M23, M31, M36, and M53 are not included in this table; see footnote 2. The maximum average annual bluff line changes for these four sites varied between +0.77 feet (+0.235 m) and -0.47 feet (-0.143).

[b] Extreme cases were eliminated by considering only those sites where rates are within two standard deviations of the mean rate.

Table 2. Results of Student's t tests indicating that statistically there is no significant difference (at the .05 significance level) in the overall rates of long-term average annual bluff crest recession between the Wisconsin and Michigan study sites.

Sample Group	# of Cases	Mean Rate	Std. Dev.	Variance	Std. Error	Student's t
Wisconsin Sites	62	1.432'	1.553	2.412	.197	.255
Michigan Sites	52	1.159'	0.963	0.927	.134	
Wisconsin Sites (normalized[a])	59	1.151'	0.930	0.865	.121	.757
Michigan Sites (normalized[a])	51	1.098'	0.863	0.745	.121	

[a] Extreme cases were eliminated by considering only those sites where rates are within two standard deviations of the mean rate.

Although the simple mean rate for each shoreland is different, 1.43 feet (0.436 m) per year for Wisconsin and 1.16 feet (0.354 m) annually for Michigan, when the values are normalized to eliminate extreme cases by considering only those sites whose rates are within two standard deviations of the mean both shorezones then display very similar rates of bluff crest retreat: an average of 1.15 feet (0.351 m) yearly for the Wisconsin bluffs and 1.10 feet (0.335 m) annually for those in Michigan.

Sites in southern portions of both lakeshores generally exhibit higher than average bluff line losses. In Wisconsin bluff crests at sites south of Port Washington (Ozaukee County) have receded at rates significantly different from those to the north of the city (Table 3 and Figure 4). Although values vary appreciably within each reach recession rates to the south (sites W1-W26), which when normalized average 1.84 feet (0.561 m) annually,[3] are much more likely to be higher than those to the north (sites W27-W62) where mean retreat is only 0.71 feet (0.216 m). In Michigan the southern reach identified by consistently high site values is restricted mostly to Berrien and Van Buren counties. But unlike sites in its Wisconsin counterpart, study locations here do not include representatives of all major shoreland types encountered within the area; although much of this zone consists of sand dunes, no study sites occur in dune locations. Furthermore, whereas sites along the northern Wisconsin shorezone display losses generally lower (but still varying) than to the south,

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[3] The exceptionally high losses incurred at sites W1-W3 were disregarded as their rates are not within two standard deviations of the mean rate. If their values are included then the mean retreat rate for the southern lakeshore is 2.43 feet (0.741 m) annually.

Table 3. Results of Student's t tests indicating that statistically there is a significant difference (at the .05 significance level) in the long-term average annual bluff crest recession rates between the Wisconin sites south of Port Washington (Ozaukee County) and those north of the city.

Sample Group	# of Cases	Mean Rate	Std. Dev.	Var-iance	Std. Error	Student's t
Sites South of Port Washington	26	2.431'	1.883	3.546	.369	.000
Sites North of Port Washington	36	0.710'	0.624	0.389	.104	
Sites South of Port Washington (normalized[a])	23	1.841'	0.916	0.845	.192	.000
Sites North of Port Washinton (normalized[a])	36	0.710'	0.624	0.389	.104	

[a] Extreme cases were eliminated by considering only those sites where rates are within two standard deviations of the mean rate.

Michigan sites north of Van Buren County are less likely to reveal this same relationship.

Several segments of both lakeshores have bluff lines that are experiencing either especially high or particularly low long-term changes (Figure 4).[4] These segments contain a comprehensive variety of shore and shoreland characteristics found within the study areas. In southern Wisconsin three shorezone stretches are identified as having sustained unusually high bluff crest recession; an equal number north of Port Washington have experienced very low losses. And three areas undergoing exceptionally high retreat and one zone sustaining minimal recession are recognized in Michigan.

Representative Areas of High Bluff Recession

Wisconsin

Bluff crest recession is highest at sites (W1-W3, Figure 4) along the southern most 3.5 miles of the Wisconsin lakeshore. Here a bluff fronting a low lacustrine terrace (Figure 5) has retreated at an average rate of 6.95 feet (2.118 m) per year. Oriented somewhat west of north the shoreline is exposed to waves generated by the potentially more damaging northeasterly storm winds which may travel over a fetch greater than 250 miles. Generally unprotected prior to 1955 (U.S. Army Corps of Engineers, 1955) shorezone protection structures now average approximately 42 per mile (Mickelson, et al., 1977) and appear to account for the wide variation in beach widths encountered over short distances.

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[4] Nevertheless, within each of these segments recession rates at individual sites may still vary appreciably. Furthermore, these reaches are not inclusive; certainly many other zones of comparable distinction go unrecognized.

Figure 5. The shorezone at site W3, South Line / Section 17 / T1N,R23E, Kenosha County, Wisconsin. Average annual bluff recession between 1835 and 1976 is 6.33 feet (1.929 m). This photo was taken on September 19, 1976.

Averaging 2.54 feet (0.774 m) yearly bluff recession is also relatively high at three adjacent section line sites (W5-W7, Figure 4) along the northern two miles of Kenosha County. This segment comprises an area discussed in detail in Chapter 4. The 30 to 35 foot high bluffs are composed primarily of water-laid sands over clay and/or till; ground water commonly discharges from the base of the sand strata at the bluff face. Protective structures are numerous along the shoreline which is oriented about 15 degrees east of north.

A third area of high bluff crest recession extends eight miles north from a point about two miles north of the Milwaukee-Ozaukee county line. Long-term retreat at eight sites (W18-W25, Figure 4) within this tract averaged 2.41 feet (0.735 m) annually. Bluffs are high, 75 to 140 feet, and are constructed of interbedded tills, clays, and water-laid sands and gravels. Ground water seeps are numerous and along many portions the bluff face is largely tree covered. Evidence of slumping is widespread on the slopes and appears to have accounted directly for bluff crest recession at many locations. At the bluff base it is large slump blocks that commonly experience storm wave erosion (Figure 6). Whereas the upper slopes of some sites have undergone significant alterations since 1968 others seem to have been relatively stable for quite some time.

Michigan

Accelerated long-term bluff recession has taken place along at least two segments of the Berrien County shorezone. One reach encompasses the Shoreham lakeside which is investigated more fully in Chapter 4 as a case study. Bluffs vary in height from about 40 to 75 feet and consist largely of water-laid sands and gravels except along the northern

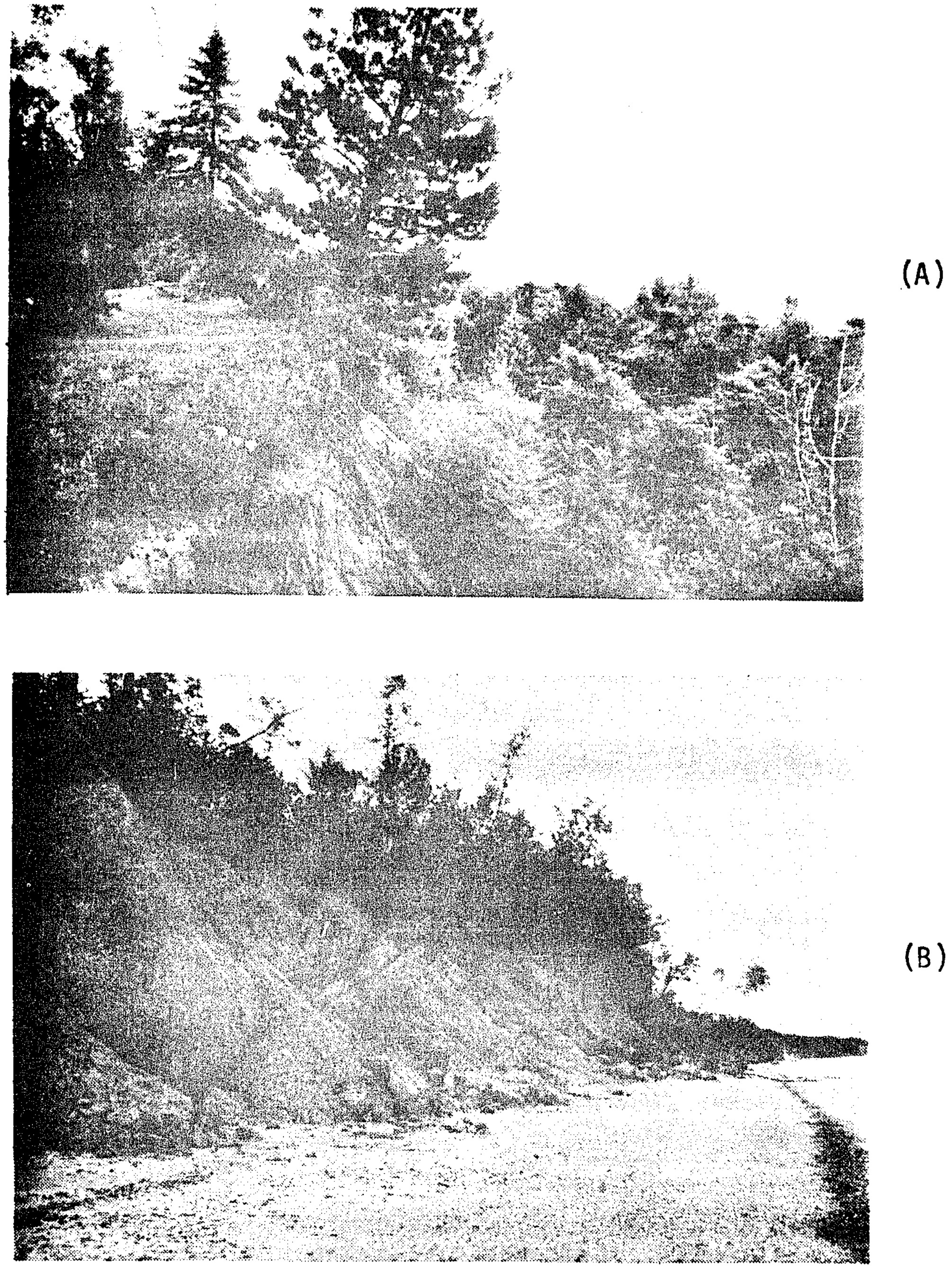

Figure 6. Bluff recession resulting from wave erosion and mass-wasting. The photos were taken in August, 1977 in Section 4 / T9N,R22E, approximately 750 feet south of site W22 (South Line / Section 33 / T10N,R22E), Ozaukee County, Wisconsin.

(A) In 1967 an 85 foot wide and 300 foot long section at the top of a 115 foot high bluff slumped down approximately 50 feet, although the block never reached the beach. Minor slumping along the top edge has continued to the present.

(B) At the base of the bluff storm waves have eroded a 20-30 foot nip into another slump block.

one-third mile where clay and/or till are interbedded with coarser clastics. For two sites (M1 and M2, Figure 4) long-term recession averages 2.02 feet (0.616 m) annually but recent rates along this lakeshore have been much greater.

Mean yearly bluff line losses of 4.30,[5] 2.92, and 2.39 feet (1.311, 0.890, and 0.728 m) are recorded for sites (M4, M5, and M6, respectively) within a three mile stretch of high bluffs beginning approximately three miles northeast of the St. Joseph-Benton Harbor jetties. Water-laid sands overlain by till and in some places topped by another relatively thin zone of water-laid sands exist in these 70 to 120 foot bluffs. Slumping, rilling, and gullying are common on the slopes (Figure 7). During the present high water period erosion of the bluff face has been severe at the southern two sites although only reaching the crest at location M4. A foredune, since removed by storm wave activity, had fronted the bluff at the northern section line and apparently delayed the onset of wave erosion on the bluff slope.

One-half mile south of the Manistee harbor jetties 60 to 70 foot bluffs (till over water-laid sands) have been receding rapidly along a 1.5 miles north-northeasterly trending shoreline. Long-term losses at two sites amounted to 1.91 and 2.65 feet (0.582 and 0.808 m, sites M43 and M44, respectively; Figure 4) annually. This high recession zone abruptly ends at and southward of the South Line / Section 15 / T21N,R17W (site M42) where foredunes have previously formed and appear to be protecting adjacent bluffs from accelerated retreat (Figure 8).

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[5] The rate at location M4 is probably somewhat higher than the adjacent bluff zone because the section line here has intercepted the bluff line at an acute angle where extensive slumping and gullying have occurred.

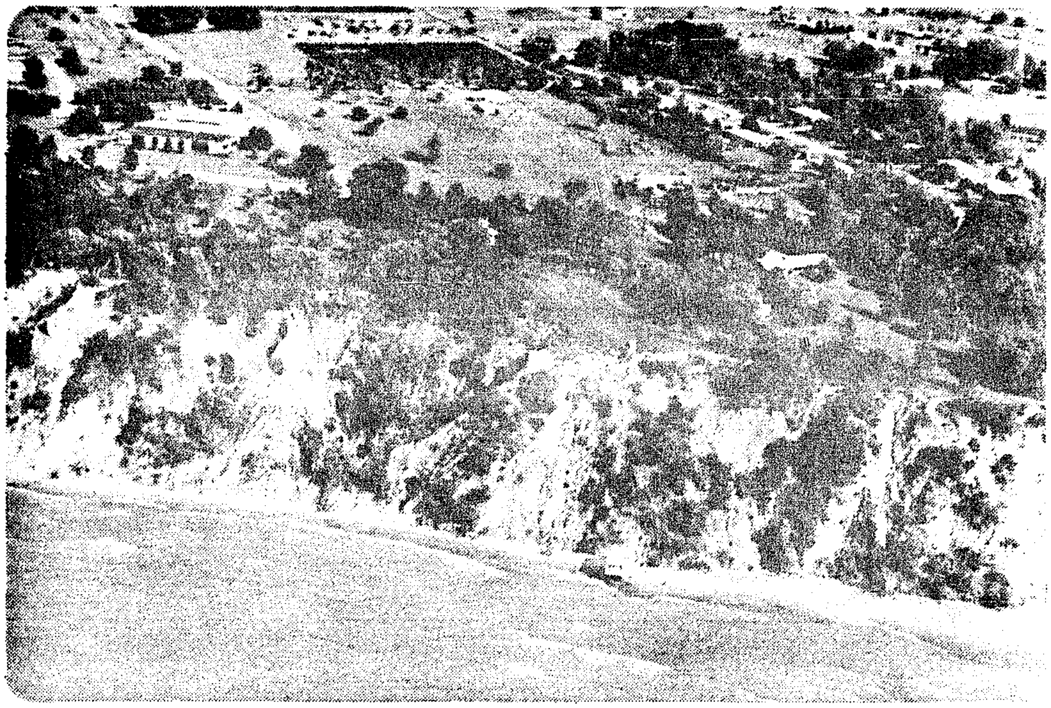

Figure 7. The shorezone at site M4, North Line / Section 6 / T4S,R18W, Berrien County, Michigan. Average annual bluff line recession between 1830 and 1977 is 4.30 feet (1.311 m). The elevated beach house was constructed sometime between 1975 and 1977. This photo was taken on August 29, 1978.

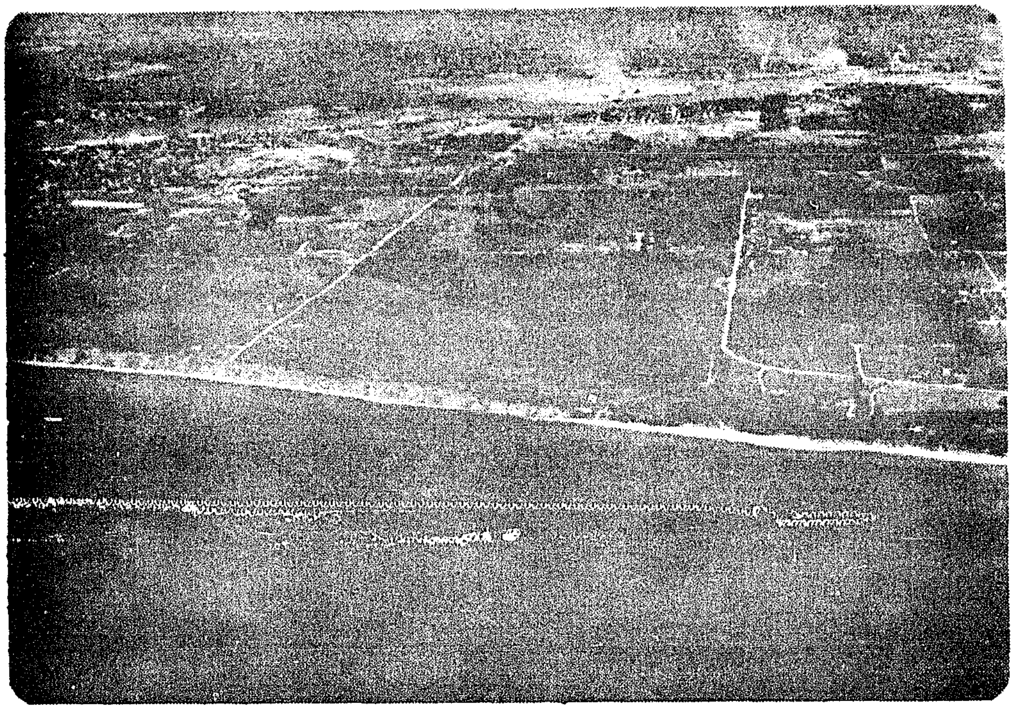

Figure 8. The shorezone at sites M42 (extension of the road on the right), South Line / Section 15 / T21N,R17W, and M43 (left road), Centerline / Section 15 / T21N,R17W, Manistee County, Michigan. Average annual bluff recession between 1839 and 1977 at site M42 is 0.52 feet (0.158 m); here foredunes have formed. Mean yearly bluff retreat at site M43 between 1847 and 1977 is 1.91 feet (0.582 m). This photo was taken on June 19, 1978.

Representative Areas of Low Bluff Recession

Wisconsin

Sites along a north-northeasterly trending shoreline from approximately Belgium Township (T12N) in northern Ozaukee County northward to the middle of Wilson Township (T14N) in southern Sheboygan County (sites W27-W35, Figure 4) have experienced relatively little long-term recession. This reach may be divided into two distinct zones. The southern portion to the Ozaukee County line is being developed on a Nipissing age lake terrace (Figure 9). Beach widths were in the 20 foot range in the summer of 1976 but residents report sand beaches 200 feet wide in the past (Hadley, et al., 1977). A 20 foot wide bedrock shelf was exposed lakeward of the beach at water level at several places (Acomb, et al., 1977; this study). And, as along the northern portion, three sand bars were evident in the nearshore zone.[6] A lake terrace also forms the northern segment but the backshore is characterized in most locations by old beach ridges and low-relief sand dunes; beaches were generally wider than to the south (Figure 10). In some areas foredunes reported by Powers (1958) in 1956-57 are no longer evident or appear to be reduced significantly in width. Shoreland recession ranging from 0.5 to 3.0 feet (0.152 to 0.914 m) per year occurred between 1967 and 1977 at several places (Hadley, et al., 1977) but mean annual long-term retreat has been much less, averaging 0.35 feet (0.107 m) for six sites considered in this study. Furthermore, three sand dune associated sites have even shown net accretion, averaging 0.16 feet (0.046 m) annually.

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[6] Sand bars are uncommon along most segments of the Wisconsin study area.

Figure 9. The shorezone at site W27, South Line / Section 25 / T12N,R22E, Ozaukee County, Wisconsin. Average annual bluff recession between 1835 and 1976 is 0.12 feet (0.037 m). This photo was taken on July 9, 1976.

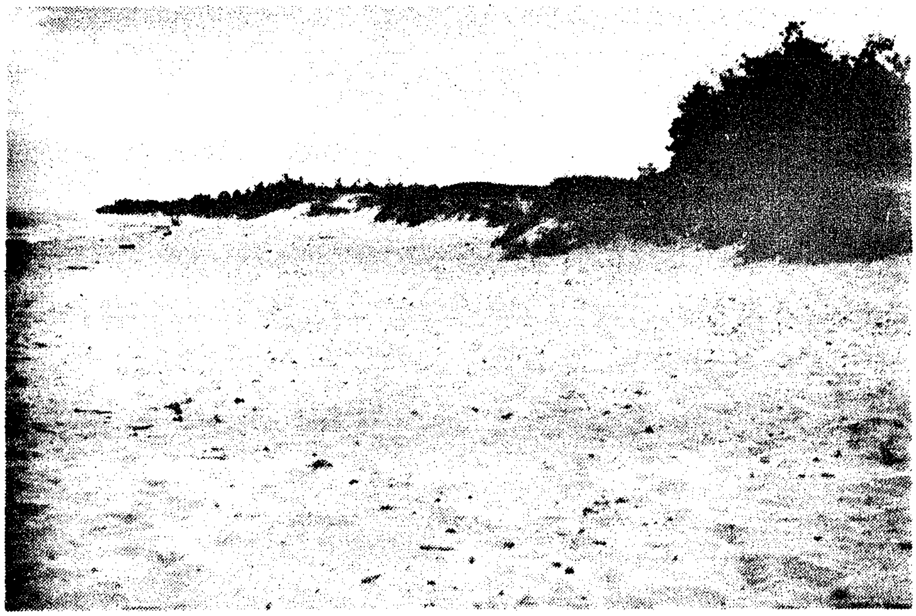

Figure 10. The shorezone at site W35, South Line / Section 14 / T14N,R23E, Sheboygan County, Wisconsin. Average annual net accretion at this sand dune location is 0.06 feet (0.018 m) for the period between 1835 and 1976. This photo was taken on August 12, 1976.

A second area with low rates of retreat exists in southern Manitowoc County and extends from midway in Centerville Township (T17N) northward to within one mile of the northern boundary of Newton Township (T18N). Average yearly recession rates at six sites (W44-W49, Figure 4) range from 0.17 to 0.76 feet (0.052 to 0.232 m). Bluff stratigraphy consists, in general, of till overlain by water-laid sands and gravels which include clay zones at some locations (Figure 11). Bluff heights at the sites range from 27.5 to 55 feet and shoreline orientation varies between N5°E and N25°E. Ground water seeps exist at the base of the sands and gravels in some places and evidence of slumping is common, although often not involving the full face of the bluff.

Bluff line changes are also relatively small at Kewaunee County sites in a zone beginning about two miles north of the Kewaunee harbor structures and extending to approximately 1.5 miles south of the Algoma jetties. These changes vary from + 0.08 feet (+ 0.024 m) a year in the north to - 0.77 feet (- 0.235 m) in the south with an overall long-term recession rate averaging 0.28 feet (0.085 m) annually for five sites (W57-W61, Figure 4). Along the southern five miles 40 to 60 foot bluffs are composed of till and sand and gravel. Slumping is common at the base of the slopes but in many places is not apparent within the upper part of the bluff (Figure 12). In contrast, a low-relief lake terrace forms the northern two miles of this low recession zone (Figure 13).

Michigan

Sand dunes are present at all Michigan sites where long-term average annual bluff line losses are less than 0.50 feet (0.152 m). The 1.75 mile shorezone segment between the outlets of North and South Bar Lakes in Leelanau County (Empire Township, T28N) is representative

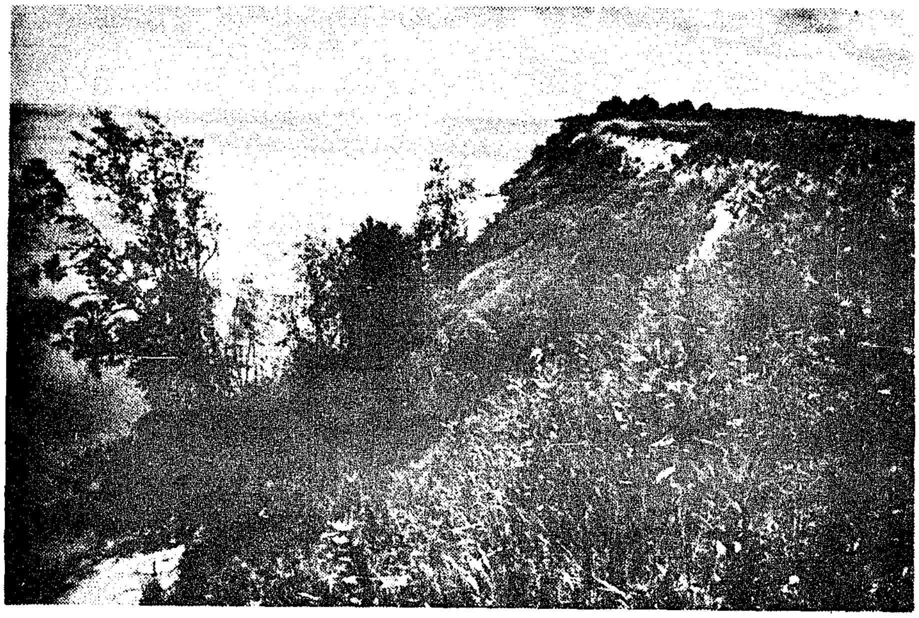

Figure 11. The shorezone at site W47, South Line / Section 24 / T18N,R23E, Manitowoc County, Wisconsin. Average annual bluff recession between 1834 and 1976 is 0.27 feet (0.082 m). This photo was taken on July 17, 1976.

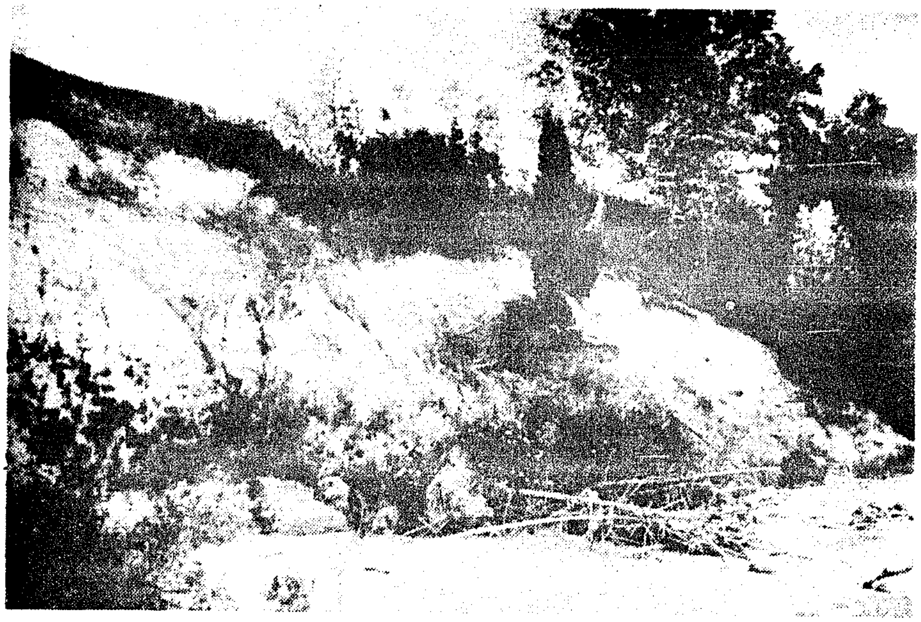

Figure 12. The bluff at site W60, South Line / Section 16 / T24N,R25E, Kewaunee County, Wisconsin. Average annual bluff recession between 1834 and 1976 is 0.22 feet (0.067 m). This photo was taken on August 7, 1976.

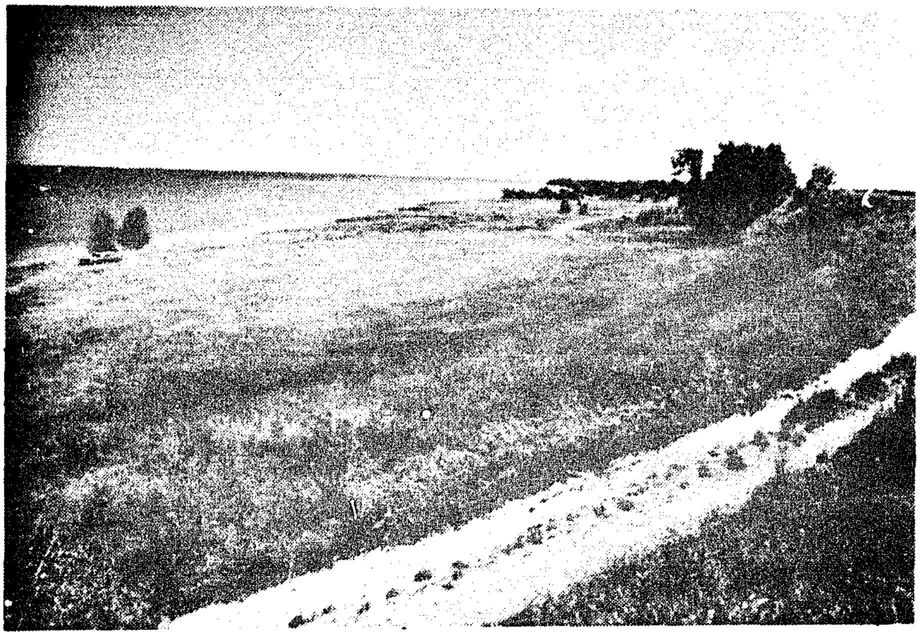

Figure 13. The lake terrace forming the shoreland along section 34 of Ahnapee Township (T25N) and sections 3 and 10 of Pierce Township (T24N), Kewaunee County, Wisconsin. Site W61 (North Line / Section 3 / T24N,R25E) is at the clump of trees on the terrace in the upper center part of the photo; measurements here indicate an average accretion value of 0.08 feet (0.024 m) annually for the period 1834 to 1976. This photo was taken on July 12, 1976.

of these locations. Mean yearly recession rates of the 13 to 15 foot high dunes[7] at the two study sites are only 0.06 and 0.34 feet (0.018 and 0.104 m; sites M51 and M52, respectively). In 1968 foredunes that formed during the low water period of the late 1950's and early 1960's fronted the more landward bluffs but, because of rising lake levels, by 1975 wave erosion had removed most of them and protective structures had been constructed along some lots (Figure 14). With a slight drop in lake elevation in 1977 a beach again developed and blowing sand began to accumulate in the backshore area.

Based on these representative areas it is apparent that many sites experiencing similar rates of long-term bluff recession have differing characteristics, and that some with similarities vary significantly with respect to their recession rates. In the following sections selected variables are examined to determine if they have clear associations with long-term retreat rates.

The Relationship of Sand Dunes and Bluff Recession

Materials comprising the bluff site profiles are grouped into four general sedimentary categories: dune sand, water-laid sand, clay, and till.[8] On this basis more than 20 different arrangements of sediments

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[7] Relative relief between the two study sites is greater, however.

[8] Dune sand: eolian deposits of sand size particles; in this study dune sand is synonymous with wind-blown sand, eolian sand, eolian sediment, eolian deposit, or eolian material.

Water-laid sand: water-deposited sand size particles, with and without pebbles, and may include thin interbedded zones with high percentage of clay or silt size particles.

Clay: water-deposited sediments of a clay or silty-clay texture.

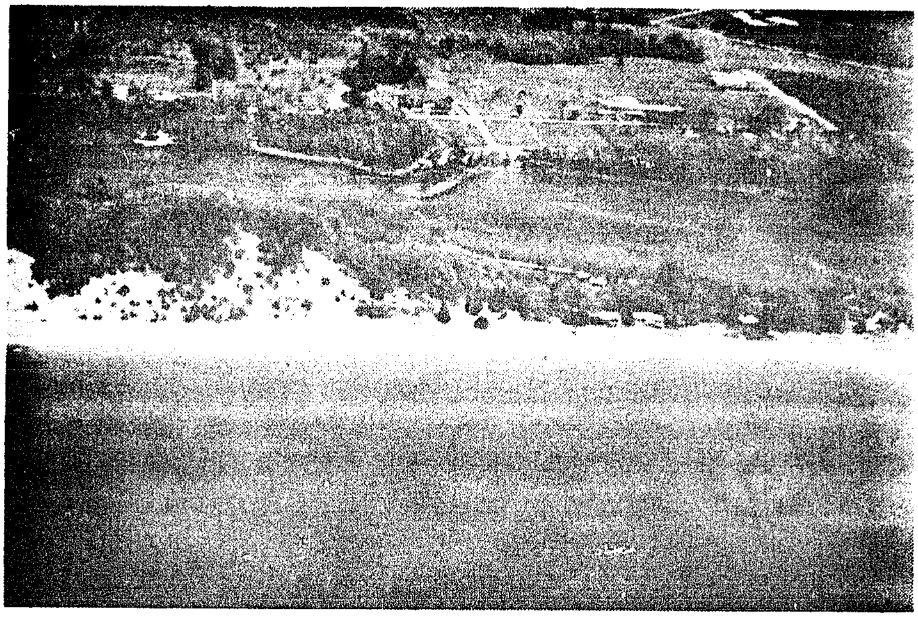
Till: non-sorted glacially deposited sediments which in the study areas are normally of a clay loam texture; pebbles and cobbles are almost always present.

Collectively, water-laid sand, clay, and till may be referred to as non-sand dune (Quaternary) sediment or material, or non-eolian (Quaternary) sediment or material.

Figure 14. The shorezone in 1968 and 1977 at site M51, South Line / Section 13 / T28N,R15W, Leelanau County, Michigan.

(A) In 1968, when the lake again began to rise above average, low foredunes, formed during the low water period of the late 1950's and early 1960's, fronted the more landward dune bluffs.

(B) Because of the above average water conditions by 1975 storm waves had eroded most of the foredunes. But with a slight drop in level by 1977 a beach had again developed. The seawall and groin system in the center of the photo was installed in the spring of 1974 and at the time stood six feet above the sand and its lakeward end was in two feet of water; by July 26, 1977 beach accretion had almost buried it.



(A) 1968

(B) July 26, 1977

Figure 14 (cont'd.).

can be identified. Variations in long-term average annual recession rates could not be related in a meaningful way to specific sedimentary types or relationships for sites where bluffs are formed of non-eolian material. Furthermore, although in Michigan the mean retreat rate for these non-dune bluffs is slightly higher and individual site values are somewhat less variable than in Wisconsin, Student's _t_ tests indicate statistically no significant difference in bluff recession rates between the two lakeshores (Table 4). There is, however, a notable dissimilarity in recession rates between bluffs formed of non-dune material and those composed of dune sand, and dune sand underlain by water-laid sand.[9] Analysis based on the difference of means _t_ test (at the .05 significance level) implies that, overall, these sand dune encompassed bluffs[10] have receded at a significantly lower annual rate than have bluffs composed of non-eolian sediments,[11] whether in Michigan or Wisconsin[12] (Tables 5, 6, 7, and 8). Moreover, between the Wisconsin and Michigan lakeshores these rates are statistically similar (Table 9).

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[9] At some locations water-laid sand is exposed at the base of an otherwise sand dune bluff. During average or low water conditions the water-laid sand may be largely obscured by foredunes but during high lake levels wave erosion reveals its existence. In Wisconsin this water-laid sand is seldom thicker than a few feet but in Michigan it may represent a zone up to several tens of feet in thickness. The surface of the water-laid sand probably represents the shore zone on which the dune sand was initially deposited. Because this surface is inclined and is at a higher elevation than the present lake level, wave erosion over hundreds or thousands of years has exposed the water-laid sand. (These bluffs of dune sand underlain by water-laid sand do not refer to the classically defined "perched sand dunes" located along portions of the northern reach of the Michigan study area.)

[10] Sand dune encompassed bluffs refer to a combination of those bluffs composed entirely of dune sand and those formed by dune sand underlain by water-laid sand.

[11] For example, of the 25 Michigan bluff sites with the lowest long-term recession rates, 18 consist entirely of dune sand and five are composed of dune sand underlain by water-laid sand.

Table 4. Results of Student's t tests indicating that statistically there is no significant difference (at the .05 significance level) in the overall rates of long-term average annual recession between Wisconsin and Michigan non-sand dune bluff sites.

Sample Group	# of Cases	Mean Rate	Std. Dev.	Var-iance	Std. Error	Student's t
Wisconsin Non-Dune Sites	52	1.611'	1.602	2.566	.222	.759
Michigan Non-Dune Sites	23	1.701'	0.912	0.832	.190	
Wisconsin Non-Dune Sites (normalized[a])	49	1.284'	0.905	0.819	.129	.146
Michigan Non-dune Sites (normalized[a])	22	1.583'	0.731	0.534	.156	

[a] Extreme cases were eliminated by considering only those sites where rates are within two standard deviations of the mean rate.

Table 5. Comparison of long-term average annual rates of recession between bluffs encompassing dune sand and bluffs composed of non-dune sediments.

Number of Sites				Long-Term Average Annual Rate of Bluff Crest Recession		
Wisconsin	Michigan	Wisconsin and Michigan		Wisconsin	Michigan	Wisconsin and Michigan
62	52	114	All Sites	1.43' (0.436 m)	1.16' (0.354 m)	1.31' (0.399 m)
59	51	110	All Sites (normalized[a])	1.15' (0.351 m)	1.10' (0.335 m)	1.13' (0.344 m)
2	20	22	Sand Dune Sites	0.02' (0.006 m)	0.60' (0.183 m)	0.55' (0.168 m)
8	9	17	Dune Sand/Water-Laid Sand Sites	0.62' (0.189 m)	1.01' (0.308 m)	0.82' (0.250 m)
10	29	39	Sand Dune Encompassed Sites[b]	0.50' (0.152 m)	0.73' (0.223 m)	0.67' (0.204 m)
52	23	75	Non-Sand Dune Sites	1.61' (0.491 m)	1.70' (0.518 m)	1.64' (0.500 m)
49	22	71	Non-Sand Dune Sites (normalized[a])	1.28' (0.390 m)	1.58' (0.482 m)	1.38' (0.421 m)

[a] Extreme cases were eliminated by considering only those sites where rates are within two standard deviations of the mean rate.

[b] Sand dune encompassed bluffs include those sites whose bluffs are composed entirely of dune sand and those formed of dune sand underlain by water-laid sand.

Table 6. Results of Student's *t* tests indicating a statistically significant difference (at the .05 significance level) in long-term average annual bluff line recession rates along the combined Michigan and Wisconsin study areas between bluffs encompassing dune sand and bluffs composed of non-sand dune sediments.

Sample Group	# of Cases	Mean Rate	Std. Dev.	Variance	Std. Error	Student's *t*
Sand Dune Sites	22	0.551'	0.824	0.679	.176	.000
Non-Dune Sites	75	1.639'	1.420	2.016	.164	
Sand Dune Sites (normalized[a])	22	0.551'	0.824	0.679	.176	.000
Non-Dune Sites (normalized[a])	71	1.377'	0.861	0.741	.102	
Dune Sand/Water-Laid Sand Sites	17	0.824'	0.712	0.507	.173	.001
Non-Dune Sites	75	1.639'	1.420	2.016	.164	
Dune Sand/Water-Laid Sand Sites (normalized[a])	17	0.824'	0.712	0.507	.173	.016
Non-Dune Sites (normalized[a])	71	1.377'	0.861	0.741	.102	
Sand Dune Encompassed Sites[b]	39	0.670'	0.779	0.607	.125	.000
Non-Dune Sites	75	1.639'	1.420	2.016	.164	
Sand Dune Encompassed Sites[b] (normalized[a])	39	0.670'	0.779	0.607	.125	.000
Non-Dune Sites (normalized[a])	71	1.377'	0.861	0.741	.102	

[a] Extreme cases were eliminated by considering only those sites where rates are within two standard deviations of the mean rate.

[b] Sand dune encompassed sites include those sites whose bluffs are composed entirely of dune sand and those formed of dune sand underlain by water-laid sand.

Table 7. Results of Student's *t* tests indicating a statistically significant difference (at the .05 significance level) in long-term average annual bluff line recession rates along the Michigan study area between bluffs encompassing dune sand and bluffs composed of non-sand dune sediments.

Sample Group	# of Cases	Mean Rate	Std. Dev.	Var- iance	Std. Error	Student's *t*
Sand Dune Sites	20	0.605'	0.838	0.702	.187	.000
Non-Dune Sites	23	1.701'	0.912	0.832	.190	
Sand Dune Sites (normalized[a])	20	0.605'	0.838	0.702	.187	.000
Non-Dune Sites (normalized[a])	22	1.583'	0.731	0.534	.156	
Dune Sand/Water-Laid Sand Sites	9	1.007'	0.567	0.321	.189	.043
Non-Dune Sites	23	1.701'	0.912	0.831	.190	
Dune Sand/Water-Laid Sand Sites (normalized[a])	9	1.007'	0.567	0.321	.189	.043
Non-Dune Sites (normalized[a])	22	1.583'	0.731	0.534	.156	
Sand Dune Encompassed Sites[b]	29	0.729'	0.777	0.604	.144	.000
Non-Dune Sites	23	1.701'	0.912	0.832	.190	
Sand Dune Encompassed Sites[b] (normalized[a])	29	0.729'	0.777	0.604	.144	.000
Non-Dune Sites (normalized[a])	22	1.583	0.731	0.534	.156	

[a] Extreme cases were eliminated by considering only those sites where rates are within two standard deviations of the mean rate.

[b] Sand dune encompassed sites include those sites whose bluffs are composed entirely of dune sand and those formed of dune sand underlain by water-laid sand.

Table 8. Results of Student's t tests indicating a statistically significant difference (at the .05 significance level) in long-term average annual bluff line recession rates along the Wisconsin study area between bluffs encompassing dune sand and bluffs composed of non-sand dune sediments.

Sample Group	# of Cases	Mean Rate	Std. Dev.	Variance	Std. Error	Student's t
Sand Dune Encompassed Sites[a]	10	0.499'	0.801	0.642	.253	.003
Non-Dune Sites	52	1.611'	1.602	2.566	.222	
Sand Dune Encompassed Sites[a] (normalized[b])	10	0.499'	0.801	0.642	.253	.014
Non-Dune Sites (normalized[b])	49	1.284'	0.905	0.819	.129	

[a] Sand dune encompassed bluff sites include those sites whose bluffs are composed entirely of dune sand and those formed of dune sand underlain by water-laid sand.

[b] Extreme cases were eliminated by considering only those sites where rates are within two standard deviations of the mean rate.

Table 9. Results of a Student's t test indicating that there is statistically no significant difference (at the .05 significance level) in the long-term average annual recession rates between the Wisconsin and Michigan bluffs encompassing dune sand (i.e., all sand dune sites and dune sand underlain by water-laid sand bluff sites).

Sample Group	# of Cases	Mean Rate	Std. Dev.	Variance	Std. Error	Student's t
Wisconsin Sand Dune Encompassed Sites	10	0.499'	0.801	0.642	.253	.428
Michigan Sand Dune Encompassed Sites	29	0.729'	0.777	0.604	.144	

[a] Because there are only two Wisconsin sand dune sites the test comparing these bluffs to Michigan's 20 sand dune sites is meaningless and is therefore not present.

Sand dune bluffs are probably no less, and may even be more, susceptible to retreat from wave erosion than are bluffs formed in non-dune material. This is supported by field and photo evidence and testimony of shorezone residents for many locations during the high water period since 1968. However, the generally lower long-term recession rates at dune sites can probably be ascribed to eolian accretion at most of these locations during lower water periods. Although this study has not monitored sites over a long time span ample evidence indicates that at many of these and other places when wide sand beaches prevail low-relief dunes (foredunes) tend to form in the backshore (Figure 15; Scott, 1942, n.d.; Olson, 1958c; Davis, Seibel, and Fox, 1973; Davis, 1976). Apparently these foredunes do not develop uniformly along the shorezone and the reason for their uneven distribution and formation is not known. In Michigan they seem to be most common along reaches where Nipissing and Algoma dune forms exist.[13] Although varying in width and height, dunes exceeding 150 feet in width and reaching heights of 10 to 12 feet and more are known to form during a single low water episode (Davis, Seibel, and Fox, 1973; Scott, 1942). In the Wisconsin study area dune accretion is for the most part restricted to two tracts, one in southern Sheboygan County and the other in the Point Beach State Park region near Two Rivers, Manitowoc County. But the dunes at these places do not approach the proportions they do on the Michigan lakeside.

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[12] This relationship was also tested and confirmed for only those sites north of Port Washington, Wisconsin and those north of the Van Buren-Allegan county line, Michigan. This eliminates the possible bias that may result because the more southerly sites along both lakeshores are largely non-dune bluffs which typically display high recession rates.

[13] However, they may also be found fronting non-dune shoreland segments.

Figure 15. Sand dune erosion and accretion between 1968 and 1977 at site M31, South Line / Section 33 / T13N,R18W, Muskegon-Oceana county line, Michigan.

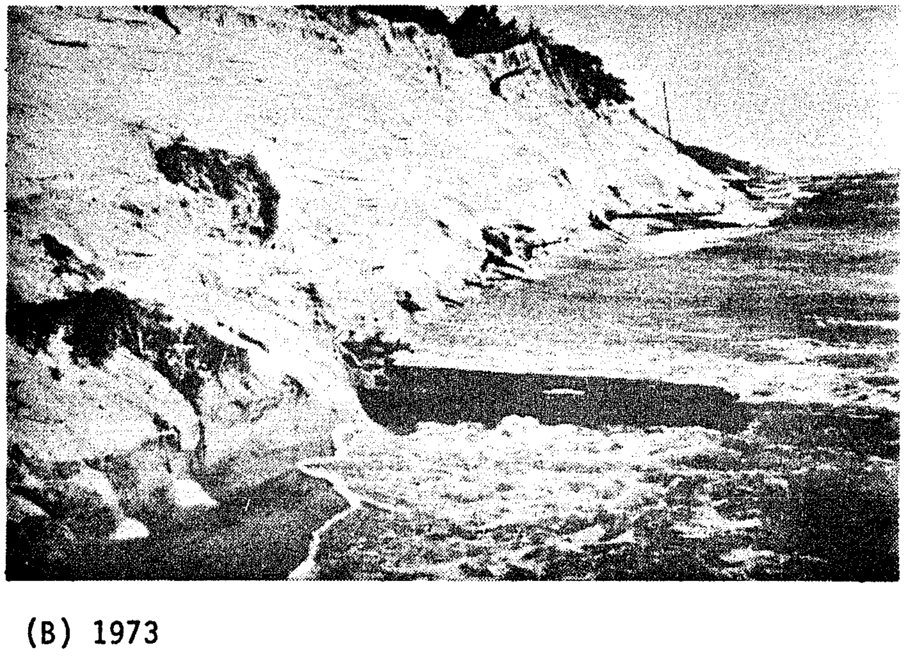
(A) 1968: Foredunes, built up during the previous decade, have just begun to undergo erosion by storm waves at the beginning of the present period of high lake levels.

(B) 1973: The lake has reached its highest level since 1886. Beaches no longer exist and the sand dunes are being severely eroded; the staircase in photo A has long since dissappeared.

(C) July, 1977: Between 1973 and 1977 the mean annual water elevation has dropped almost two feet, beaches have again developed, and eolian sand is beginning to accumulate in the backshore.

(D) September, 1978: Although the lake level has risen slightly from the year before and beaches are somewhat narrower, actively accreting foredunes have established themselves fronting the previously eroded dune bluff.

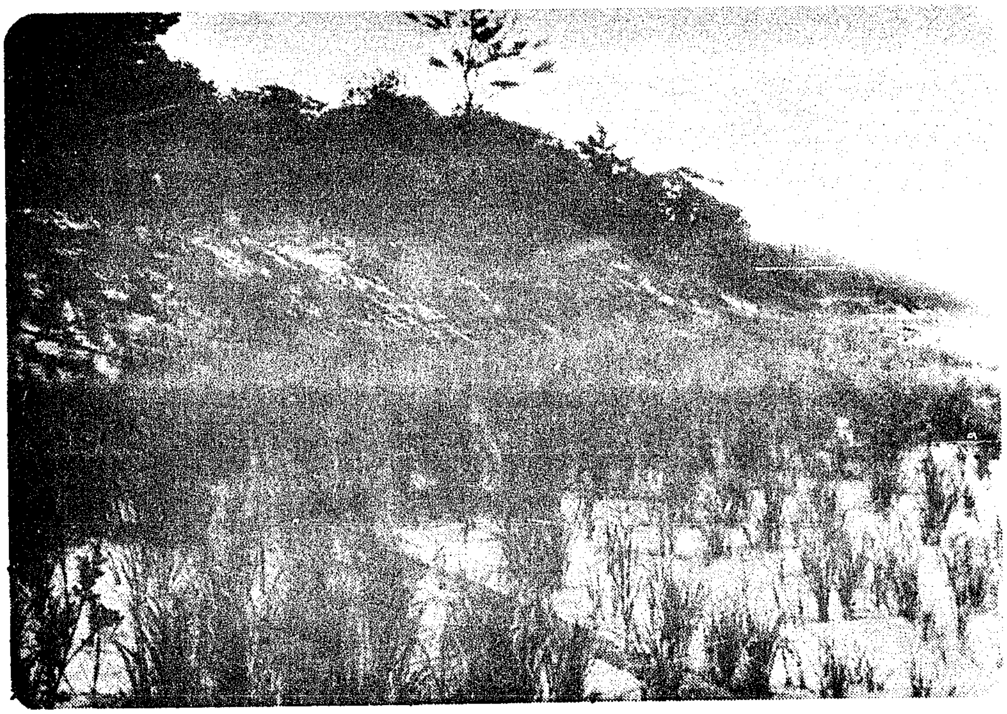
(A) 1968



(B) 1973

Figure 15 (cont'd.).

(C) July, 1977



(D) September, 1978

Figure 15. (cont'd.).

The relative effectiveness of foredunes in delaying bluff line recession once high lake levels allow accelerated wave erosion to begin may be illustrated. Twenty[14] Michigan dune and non-dune bluff sites which experienced long-term recession exhibited no crest retreat during the 1968 to 1977 high water stage. Fifteen[15] of the 20 were fronted in 1976-77 by a foredune or by one in 1968[16] at the beginning of the high water period.

Not all sand dune sites exhibit low recession rates; furthermore, sites experiencing low rates are not necessarily characterized by dunes. Where conditions no longer allow adequate sand replenishment during low water periods dune sites can exhibit substantial net losses. This may happen when the construction of groins or jetties prevent littoral drift from reaching the dune area.

It is curious that the shoreline of the eastern study area appears on the whole so smooth, even though both recession rates and physiography vary significantly along the lakeshore. For example, data show that long-term recession rates at non-dune sites tend to be twice as great as at dune sites, suggesting that shoreline configuration should reflect these differential rates. But this appears not to be the case; most of the dune areas do not protrude lakeward nor are most non-dune shoreland segments embayed. A smooth outline, however, was

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[14] Four of the 20 are the double-crested dune sites M23, M31, M36, and M53.

[15] The other five have bluffs whose heights equaled or exceeded 69 feet; see "Bluff Height" in the following section.

[16] This was confirmed by examination of 1968 Michigan Department of Natural Resources oblique color slides of each site location.

not associated with some of Lake Michigan's ancestral lakes. Shorelines of higher proglacial lakes, notably Lakes Algonquin (11,500 years BP) and Nipissing (4,000 years BP), embodied numerous embayments. Furthermore, most of the present day sand dunes are associated with the ancestral embayments (Scott, 1942; n.d.).

Apparently the smooth shoreline of modern Lake Michigan is dually attributed to the accumulation of sand dunes in these indentations as the ancestral lakes changed elevation and to the accelerated retreat of the non-eolian shoreland segments separating the embayments. The fact that this study found significant differences in long-term recession rates between dune and non-dune bluffs suggests that this shoreline only most recently attained its present degree of smoothness. This smoothness, however, is relative and its awareness depends to a large degree on scale. When compared historically, and viewed on a small scale, the shoreline has indeed become much less irregular. But on a large scale this smoothness is less striking and its perception may be attributed to the ratio between the distance (in thousands of feet) separating adjacent study sites and their recession values (in tens and hundreds of feet). This ratio is large enough that the shoreline would appear smooth, even though there are differential recession rates taking place.

In summary, during higher lake stages low foredunes may quickly come under attack by storm waves but their presence may prevent or delay erosion on the landward shoreland. Furthermore, when the lake level dropsforedunes can generally be expected to form once again in those areas where they existed previously, provided shorezone conditions have remained similar. However, as a consequence of the periodic nature of these accretionary and erosional events, at sand dune locations net long-term recession rates tend to be lower but gross long-term losses may be greater than at non-dune sites.

Relationship of Bluff Recession to Other Selected Variables

Ground Water

While ground water activity cannot be directly correlated with rates of recession it does seem to be an important variable in the mechanics of bluff crest retreat at many sites. It is important to note that most bluff recession takes place through slope failure. While this may be initiated by wave erosion at the bluff toe ground water within the bluff itself is often a critical factor contributing to instability (Savage, 1968; Bird and Armstrong, 1970; Selby, 1970; Hadley, 1974, 1976; Gray, 1975; Great Lakes Basin Commission, 1977; Mickelson, et al., 1977; Vallejo, 1977; and others). Subsurface water has several destabilizing effects which may independently or in unison cause slope failure. First, it increases porewater pressure and decreases the cohesiveness and shear strength of the bluff material. Second, it tends to move downward through permeable layers until relatively impermeable zones are encountered and some water is then diverted along this horizon toward the bluff face. The force of the ground water discharge at the face can remove granular particles from the permeable bed and thus eventually remove support for overlying sediments. And, third, large quantities of ground water can cause high shear stress within the slopes because it increases the unit weight of the bluff material.

Perched water conditions are largely confined to bluffs composed of multiple sediment layers of different permeabilities; they are rarely found in dune bluffs. Fifty-eight percent of the Wisconsin bluff profiles include both permeable and relatively impermeable strata; this circumstance exists at only 34% of the Michigan locations. Furthermore, ground water was detected discharging from the bluff face at twice as many sites in Wisconsin as in Michigan. These facts and other observations suggest that, on the whole, ground water seepage is probably more detrimental to the maintenance of bluff slope stability along the Wisconsin lakeshore than along the Michigan shore.

The bluff segment encompassing sites W18-W24 in southern Ozaukee County, Wisconsin illustrates the aforementioned condition. Throughout this tract are very large slump blocks, usually still vegetated, resting at the base of the bluff[17] (Figure 6). Ground water discharge is evident at most locations and it is not uncommon for it to pond on the upper surface of the slump block. Even though the blocks protect the bluff from further erosion many of the bluff crests appear to be still actively retreating due to slope failure above the level of the slump blocks. It is highly likely that instability caused by ground water seepage contributes significantly to the high long-term bluff recession rates recorded in this location.

Ground water performs an important function in bluff slope evolution in other areas along the Wisconsin lakeshore (Edil and Vallejo, 1977; Vallejo, 1977; Mickelson, et al., 1977). For instance, Whitney (1936) demonstrated that a section of till bluffs north of Milwaukee failed primarily because of ground water activity. And Hadley (1974) states that it contributes significantly to the slumping and high bluff line recession along Bender Park in southern Milwaukee County (site W13).

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[17] In 1918 Alden reported that this shorezone segment in Ozaukee County was experiencing "much slumping down of the bluff in places" (p. 338).

Bluff Height

Even though banks of increasing heights provide a greater potential volume of sediments data show that long-term recession rates appear not to be related directly to bluff height. On a short-term basis, however, high banks may show far less, or more, crest recession than low bluffs. Because the horizontal distance between base and crest is greater for high than low bluffs a longer time may be needed for initiation of crest retreat on the higher banks once accelerated erosion begins. This situation is especially apparent on bluffs whose profiles contain thick sequences of more cohesive sediments. For example, of the eight Michigan sites with bluffs over 100 feet, five displayed no recent crest recession even though their long-term losses ranged from 0.80 to 2.92 feet (0.244 to 0.890 m) annually. Although one was previously protected by a foredune the remaining four were not. Each of these bluffs had experienced appreciable toe erosion resulting in an over-steepened slope. But the crest line area of each had not receded, apparently because the upper slope material was cohesive enough to remain standing at a high angle. This condition might possibly last longer than a single high water period. When the upper slope does fail, however, crest retreat may be relatively great; in a single event the bluff line could recede as much as a low bluff crest did over a five or ten year period. In other cases, when lake levels drop and wave erosion diminishes, high bluff slopes may be expected to establish equilibrium profiles less rapidly than low bluff faces because the higher crests must recede a greater distance for slopes to become stable. Therefore, it would not be unusual for mass-movement, accompanied by subsequent crest retreat, to continue on the higher bluff slopes for some time after it had halted on the low bluffs.

The lack of correlation found between heights and long-term recession rates on non-dune bluffs may also be attributed, in part, to ground water. In non-dune areas the higher the bluff the more likely its stratigraphy is composed of both permeable and relatively impermeable sediments, resulting in a higher probability for perched water tables. In this study ground water seeps were detected in most bluffs more than 50 feet in height.

In summary, for slopes of high bluffs to reach stable angles once accelerated wave erosion ceases, their crest lines must retreat longer distances over greater time than those of low banks. Thus, crests of high bluffs will most likely retreat greater distances in a single event than do crests of low bluffs. As a result there may be very little difference in the long-term recession between high and low bluff crests.

Shorezone Protection Structures

Although not demonstrated quantitatively, field observations for this study support conclusions reached by other investigators (Larsen, 1972; Davis, Seibel, and Fox, 1973; U.S. Army Corps of Engineers, 1973, 1974; Omohundro, 1973; League of Women Voters, 1974; Hadley, 1976) that shorezone protection devices commonly cause undesirable aberrations in beach, bluff, and/or nearshore conditions. Measuring, and even recognizing, the full impact that these structures have on the lakeshore is difficult, but observations show that many of these devices prompt abnormally high erosion and/or accretion in areas adjacent to them.

The protection structures most commonly erected along the shorezone may be divided into two groups--groins and jetties, and seawalls and revetments. Because groins and jetties tend to extend perpendicularly from the shoreline they restrict passage of littoral drift. Beaches thus tend to widen on their updrift side through trapping but narrow on the downdrift side of the structure because the supply of sediments is reduced or eliminated. With time beaches in these downdrift areas usually become increasingly meager and may be unable to adequately protect the shoreland from storm waves, possibly resulting in accelerated bluff recession. This condition is known to exist at sites M1, M2, and M8 where high bluff retreats are partially attributed to the adverse effects of harbor jetties (U.S. Army Corps of Engineers, 1973; 1974).

Seawalls and revetments are generally located parallel to the base of shoreland bluffs to protect them against erosion by incoming waves. Unfortunately, the scouring effect of the breaking waves normally results in deeper water conditions lakeward of the structures. As a consequence even when relatively wide beaches form nearby they seldom develop in front of seawalls and revetments. More importantly, because adjacent unprotected bluffs may recede at greater rates, the armored tracts commonly become promontories. Without periodic repair and extension, however, the structures are eventually flanked by storm waves and their effectiveness destroyed.

Shoreline Orientation

Shoreline trends at the study sites vary by almost 100 degrees (see Appendix B, Tables B1 and B2). In Wisconsin they range between N48°W and N48½°E whereas in Michigan they vary from N30°W to N38°E.[18]

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[18] Shoreline orientation is based on lakeshore segments extending a quarter mile to each side of the site. Statistical analysis in this section is based on data for only those locations where shoreline trend is similar on both sides of the site; this criterion eliminates a few sites where shorelines have a concave or convex configuration but their exclusion does not affect the conclusions reached.

Michigan sites were separated into two categories, one with shoreline trends in the northwest quadrant and the other with orientations toward the northeast. The average yearly retreat value for northwesterly oriented sites is 0.88 feet while the rate for northeasterly trending locations is 1.51 feet.[19] Student's *t* tests indicate that average bluff loss between these two groups is statistically different.[20]

Examination of Wisconsin data reveals a tendency for recession rates to differ when sites are separated based on a N10°E trend line. The mean retreat rate for locations where the orientation is westward of N10°E is 2.15 feet yearly.[21] For those sites whose trend is eastward of N10°E, the average rate is only 0.90 feet. Student's *t* analysis establishes that the rates between the two groups are significantly different.[22]

The Michigan and Wisconsin trend categories with the higher retreat rates correspond to sites likely to experience more direct exposure to high energy storm waves. In Wisconsin the most damaging winds are generally from the northeast quadrant (Hadley, 1976; Mickelson, et al., 1977) and on the Michigan lakeshore northwesterly storm winds are commonly the most destructive and longest lasting (Jay Harman, personal communication). However, the relative importance of these orientations is rendered less

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[19] If only sites whose rates are within two standard deviations of the mean are considered, the rate is 1.39 feet annually.

[20] Student's *t* is 0.026; if only sites whose rates are within two standard deviations of the mean are considered, Student's *t* is 0.046. The level of significance was established as 0.05.

[21] If only sites whose rates are within two standard deviations of the mean are considered, the rate is then only 1.55 feet annually.

[22] Student's *t* is 0.005; if only sites whose rates are within two standard deviations are considered, Student's *t* is 0.018. The level of significance was established as 0.05.

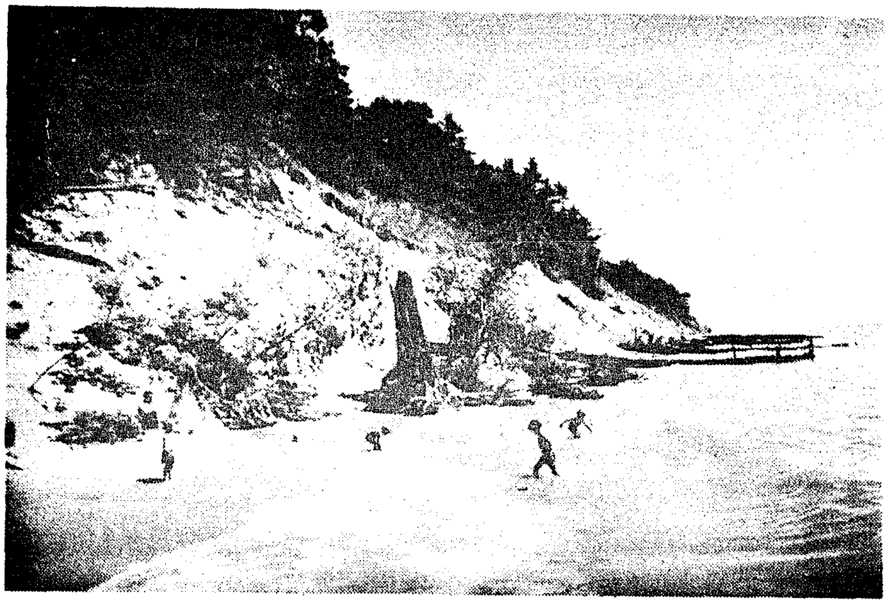
clear by the fact that the majority of the northwesterly trending sites in Wisconsin and the northeasterly oriented sites in Michigan are located in the southern portion of the lake basin. The relatively large fetches over which the major storm winds can travel and waves develop may be as much, or more, influential for accelerated bluff recession than the orientation of the shoreline.

Beach Width

Beach conditions are influenced by lake level, sediment sources, littoral currents, weather conditions, shorezone structures, and nearshore slopes. Changes in any one of these may substantially alter beach characteristics and therefore its ability to protect lakeshore bluffs against storm wave erosion. Although direct relationships between beach widths and long-term bluff recession rates are not established in this study, many field observations, as exemplified by Figure 16, clearly illustrate the important function performed by the beach.

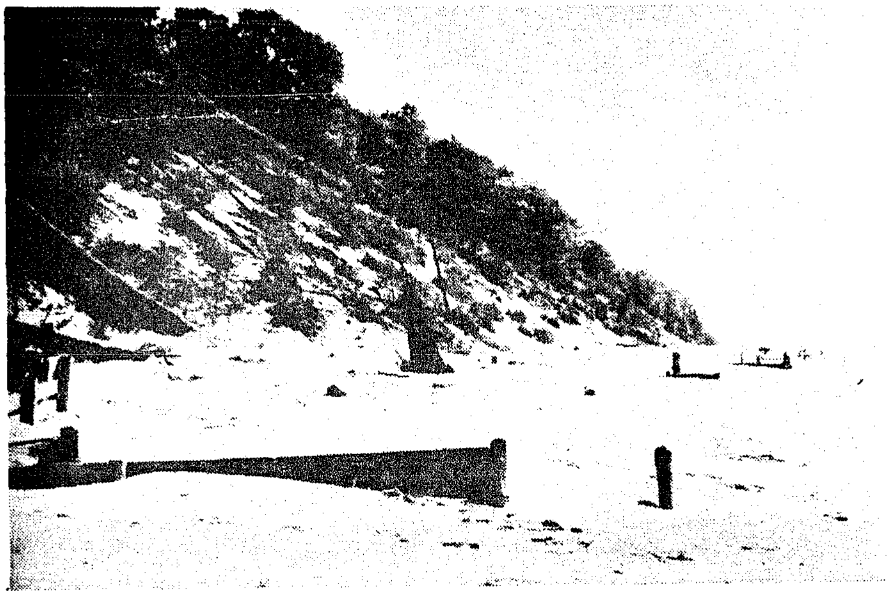
Implication of Other Factors

It is obvious that the land oriented variables considered in this study are adequate to account for much of the spatial variation in shoreland recession, and even when recognized their relative importance is questionable. Success in understanding the causal factors in bluff erosion is probably better met if the investigation is extended into the near- and offshore environments. It seems likely that point-to-point variations in bluff retreat are linked to differences in wave energy distribution along the shore and to such factors as localized eddies and currents, nearshore sand bars, reefs and bottom irregularities, and littoral drift.



(A) July 4, 1973

Figure 16. Variation in beach widths at the South Line / Section 15 / T12N,R18W, Muskegon County, Michigan, 1973-1977. In July, 1973 (photo A) Lake Michigan's monthly level averaged 580.98 feet. No beach existed and the bluff was very susceptible to storm wave erosion. By September, 1976 (photo B; average monthly water level:579.92 feet) and continuing through July, 1977 (photo C; mean monthly lake elevation: 578.57 feet) the lake surface had dropped (although remaining above average) and protecting beaches had formed.



(B) September 30, 1976

(C) July 3, 1977

Figure 16 (cont'd.).

Other investigators have reached similar conclusions. Davis (1976), Davis, Seibel, and Fox (1973), Fox and Davis (1973), and Saylor and Hands (1970) suggest that beach and bluff changes are related to the interaction of incoming storm waves and the nearshore sand bar system. Gelinas and Quigley (1973) report that the total wave energy reaching a portion of the Lake Erie shoreline correlates well with long-term average rates of erosion. And for a three-kilometer reach in southwestern Michigan Maresca (1975, pp. 145 and 158) demonstrates that

> total bluff line recession and beach erosion are dependent upon the complex interaction of the total energy distributed along the shoreline and the resulting transport of sediments offshore and alongside

and that

> the distribution of wave energy along the shoreline depends on the convergence and divergence of wave energy due to wave refraction, the unequal dissipation of the wave energy before the wave breaks on the shore, and the balance or imbalance of the alongshore transport of material.

Furthermore, in a recent report on bluff recession in Racine County, Wisconsin Keillor and DeGroot (1978, p. 3) state that

> irregular bottom features, bars and reefs modify the path that waves take towards shore. These natural underwater landforms can cause wave energy to concentrate, or spread out and dissipate on local beaches. The patterns vary depending on direction of approaching waves and on wave conditions.[23]

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[23] Keillor and DeGroot had constructed wave refraction diagrams for dominant NNE storm waves and found that wave energy is more dispersed along the shore south of Wind Point than to the north. The Point and nearby submerged reefs partially protected the southern reach from the full impact of the storm waves. The less protected northern segment correspondingly experienced greater bluff recession than to the south. The relative difference in recession rates between these two shorezone segments is illustrated by the rates determined for sites W8-W13 in this study.

The relationship between bluff recession rates and nearshore bathymetry and wave and current activity is complex. Data are not readily available and success in establishing the significance of the correlation on a lakewide basis awaits further investigation.

Assessment of Factors Influencing Large-Scale Patterns in Bluff Recession Rates

Several especially important findings of this study deserve assessment: first, the unexpected similarity in overall long-term bluff line recession rates between the Michigan and Wisconsin shorelands; second, the tendency for sites in the southern portion of each study area to exhibit above average bluff losses; and third, the significantly lower recession rates along Wisconsin's northern as compared to southern lakeshore.

Both study areas periodically experience severe storm winds and waves, although total yearly energy from incoming deep water storm waves is greater on the Michigan lakeside (Saville, 1953; Davis and Fox, 1974). Apparently, however, the better development of longshore sand bars (Hands, 1970; 1976) and beaches (Krumbein, 1950; Hulsey, 1962) on the eastern margin lessens incoming shallow water wave energy and may reduce potential long-term bluff recession rates. Furthermore, because of many more dune sites on the eastern lakeside, Michigan's mean recession rate reflects more strongly the influence of foredune regeneration and consequently is a lower value than would be expected had not foredunes intermittently formed. Moreover, on the Wisconsin shorezone a higher incidence of conditions detrimental to bluff slope stability[24] seems to

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[24] These conditions are caused more notably by ground water within bluffs of multiple sediment layers of different permeabilities.

prevail, a situation that would tend to amplify retreat rates on Wisconsin's shoreland. This combination of factors may well result in similar overall average annual bluff recession rates for the two lakeshores.

The higher retreat rates experienced by sites along the southern portion of each state are likely due to a combination of several factors: the dominant storm winds affecting Lake Michigan, the large fetches over which they travel, and shoreline trends which tend to be more normal than parallel to the prevailing storm waves. Because wave size is directly related to wind velocity, wind duration, and fetch, storm wave development, and therefore wave energy and potential erosional ability, is likely to be greatest along these reaches.

In addition to differences in dominant storm winds, in Wisconsin several other factors may influence the significantly lower average recession rates found at most sites north of Port Washington; the relative importance of each of these variables is unknown, however. For one, the overall shoreline trend north of Port Washington approaches north-northeast, which places it more parallel than normal to the dominant northeasterly storm winds and waves.[25] Southeasterly winds would potentially be more damaging but storm winds from that direction

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[25] The major exception to this north-northeasterly trend is the northern headland portion of Point Beach State Forest, Manitowoc County, where the shoreline is oriented north-northwest. The beach ridges that form the headland have been severely eroded here; Gorder (1975) estimated an average loss of about three feet per year during the last 3,000 years. In the present investigation the two northern study sites with the highest recession rates (W52, 2.63 feet/year; W53, 1.77 feet/year) are located in the vicinity. The northeasterly trending southern portion of the headland appears to be protected by beaches whose sands have come by way of longshore currents from the eroded beach ridges in the northern part of the headland (Paull and Paull, 1977).

are uncommon. Secondly, nearshore bedrock reefs are known to exist in places along the northern reach, as are longshore sand bars; both features may reduce incoming wave energy and retard bluff losses. Thirdly, for extended lengths north of Sheboygan nearshore bottom slopes appear to be more gentle than are slopes south of Sheboygan to Milwaukee. And lastly, along this northern shore are found the two Wisconsin sand dune tracts. The low long-term recession rates in these dune reaches are statistically similar to those in dune areas on the Michigan side of the lake. In contrast, significant differences in recession rates between sites in the northern and southern portions of Michigan are not likely. Not only are northern and southern shorezone characteristics more similar than on the Wisconsin side but the Michigan lakeshore is influenced by strong storm winds and waves from both the southwest and northwest quadrants (although total yearly wave energy is relatively greater from the northwest quadrant).

Summary

The following summary statements are based on site data and related observations.

(1) Site data indicate that overall long-term bluff recession along the Wisconsin and Michigan shorezones is statistically similar.

(2) Non-sand dune sites along the southern portion of both lakeshores tend to be experiencing relatively rapid long-term retreat.

(3) Wisconsin bluffs at sites south of Port Washington (Ozaukee County) are receding at rates significantly higher than those at study locations north of the city.

(4) On the whole, sand dune bluffs are receding at significantly lower rates than are bluffs composed of non-dune sediments. These generally lower long-term values can probably be attributed to dune accretion at most of these locations during lower lake stages.

(5) Long-term bluff recession rates cannot be correlated with specific sediments or sediment arrangements for those sites whose bluffs are composed of non-eolian material.

(6) Data on ground water activity and bluff height cannot be directly related to varying rates of long-term recession. However, ground water seepage appears to be an important contributor to bluff slope instability, and because it is prevalent in most high non-dune bluffs, it may at least partially account for the lack of correlation between retreat values and bluff heights.

(7) Shoreline orientation, coupled with fetch, appears to influence rates of bluff recession.

(8) Beach widths cannot be meaningfully related to long-term retreat values.

(9) It is apparent that lakeside protection structures interfere with natural shorezone processes. Although their effect may be locally beneficial, they commonly initiate adverse conditions elsewhere, especially in adjacent and/or downdrift locations.

Chapter 4

MODERN RATES OF BLUFF RECESSION AND THEIR FUTURE IMPLICATIONS: TWO CASE STUDIES

Introduction

In the context of two case study areas the objectives of this chapter are: (1) to determine bluff losses during approximately the last four decades, (2) to illustrate the effects shorezone protection structures can have on bluff retreat and lakeshore conditions, and (3) to discuss and predict future bluff positions and their consequences. The first case study segment consists of the 1.4 mile long lakeshore of the Village of Shoreham, Berrien County, Michigan. The second area encompasses the Lake Michigan shorezone in the northern two sections of Kenosha County, Wisconsin (Figure 4). These localities were chosen because: (1) based on section line sites, they represent shorelands experiencing above average long-term bluff recession; (2) numerous residential and commercial structures have been destroyed and many are threatened by bluff erosion; (3) bluff lines are generally well-defined; and (4) relatively good quality stereo-paired aerial photos are available for several years since 1938 from which recession rates can be determined.

Determination of Recession Rates

Modern recession values were determined photogrammetrically by comparing bluff line positions on older panchromatic stereo-paired aerial photography with positions on more recent imagery. The photos were precisely scaled by field measurements of features found both on the ground and on the aerial imagery. Retreat rates are ascertained for the following periods:

Shoreham, Michigan	N. Kenosha County, Wisconsin
1938 to 1977	1941 to 1975
1938 to 1967	1941 to 1969
1967 to 1977	1969 to 1975

The 1975 and 1977 photos represent available recent imagery whereas those of 1938 and 1941 are among the earliest taken of the study areas. The 1967 and 1969 photos are those available with dates nearest the beginning of the present high lake stage. Imagery covering other years were also examined in order to study visually the sequential development of the bluff zone.[1] Table 10 lists the photographs used.

At 15 places in Shoreham and 22 in Kenosha County identical features near the bluff edge were recognized on both the 1967 and 1977 or 1969 and 1975 photos (respectively). For each of the two years distances trending east-west from these landmarks to the bluff crest were measured using either a 7X Alan Gordon Pocket Comparator with unit increments of 0.1 mm or a 12-inch Gurley Rapid Comparator with divisional units of 0.005 inches. The difference, converted to ground distance in feet, between the two measurements indicated bluff line losses between the two dates. The margin of error is calculated to be within 3.5 feet.

Because few features identical to both 1966 and 1938 or 1975 and 1941 photos are recognizable, a Bausch and Lomb Zoom Transfer Scope (ZTS) was utilized to ascertain recession rates between these years.

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[1] Recession rates were not established based on these photos. Because of their small scale and the relatively few years between each photo set, any determined recession rate could have been less than the margin of error inherent in the measurement technique.

Table 10. Aerial photos utilized for the Shoreham, Michigan, and northern Kenosha County, Wisconsin, case study investigations.

	Date	Source[a]	Nominal Scale	Imagery Code and Frame Numbers
Shoreham, Michigan				
Photos Used For Measurements	4/27/77	MDSHT	1:12,000	FEG-5 to 7, 15 to 17
	9/11/67	ASCS	1:20,000	AIT-4HH-2 to 5
	6/ 5/38	NARS	1:20,000	AIT-4-31 to 34
Other Photos Examined	9/25/74	ASCS	1:40,000	26021 174-238 to 240
	5/31/60	ASCS	1:20,000	AIT-3AA-126 to 128
	7/24/55	ASCS	1:20,000	AIT-5P-14 to 16
	8/ 5/50	ASCS	1:20,000	AIT-5G-110 to 113
N. Kenosha Co., Wisconsin				
Photos Used For Measurements	5/27/75	WDNR	1:12,000	BW28-36 to 39
	8/28/69	ASCS	1:20,000	XC-1KK-49 to 53
	10/28/41	NARS	1:20,000	XD-2B-62 to 65
Other Photos Examined	6/24/63	ASCS	1:20,000	XD-1DD-42 to 45
	8/14/56	ASCS	1:20,000	XD-1R-30 to 33
	9/ 6/50	ASCS	1:20,000	XC-1G-24 to 27
	8/12/37	NARS	1:20,000	XD-25-2296 to 2298

[a] MDSHT - Michigan Department of State Highways and Transportation
ASCS - Agricultural Stabilization and Conservation Service, United State Department of Agriculture
NARS - National Archives and Record Service
WDNR - Wisconsin Department of National Resources

By using the ZTS the older photos were superimposed on the larger-scaled recent imagery. Then at the aforementioned 15 and 22 sites bluff recession was determined by measuring the difference between crest positions for the different years with a Pickett Pocket Rule scaled in 0.01 inch increments. An estimated error of less than 10 feet is possible. It was then a simple matter to calculate recession values for the periods 1938 to 1967 and 1941 to 1969.

The Shoreham Case Study

Characteristics

Evidenced by recent losses exceeding 100 feet in places, houses toppling into the lake, and numerous shore protection devices, Shoreham is undergoing especially severe bluff recession (Figure 17). Fifty to 60 feet in height, the bluffs are composed of variable water-laid sediments including loamy sand, sandy loam, and silty loam; ground water seeps occur at the top of some of the finer sediment zones. Overall shoreline orientation is about N26^{o}E; this trend may contribute to accelerated erosion as approximately twice as much yearly energy is derived from waves from the south-southwest through west (U.S. Army Corps of Engineers, 1973b).

Bluff recession at Shoreham has been accelerated by effects of the Federal harbor jetties three miles north of the area at the mouth of the St. Joseph River (U.S. Army Corps of Engineers, 1973; Linney, 1976). These two structures interrupt the southward littoral movement and lessen sand nourishment to beaches downdrift.[2] Constructed,

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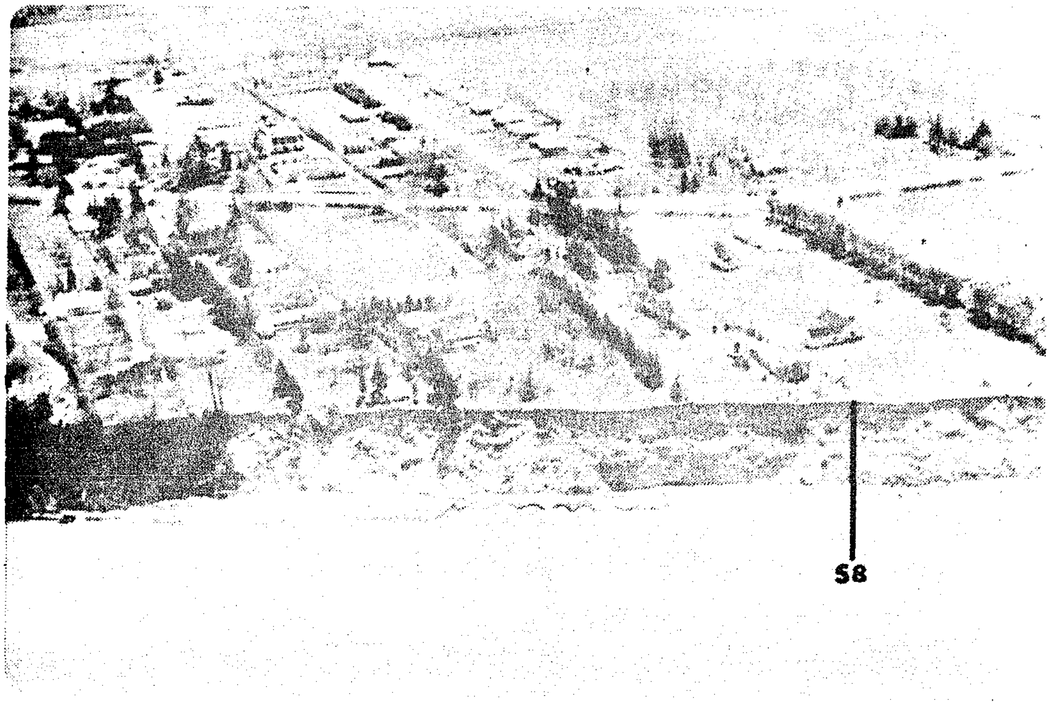
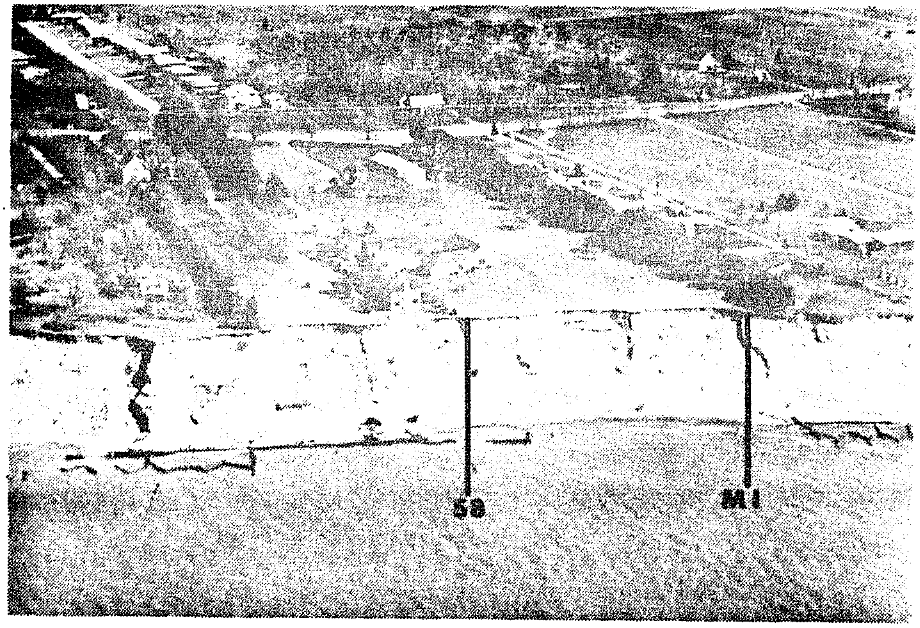
[2] Little or no beach building material presently passes naturally across the harbor entrance to the downdrift shore (U.S. Army Corps of Engineers, 1958).

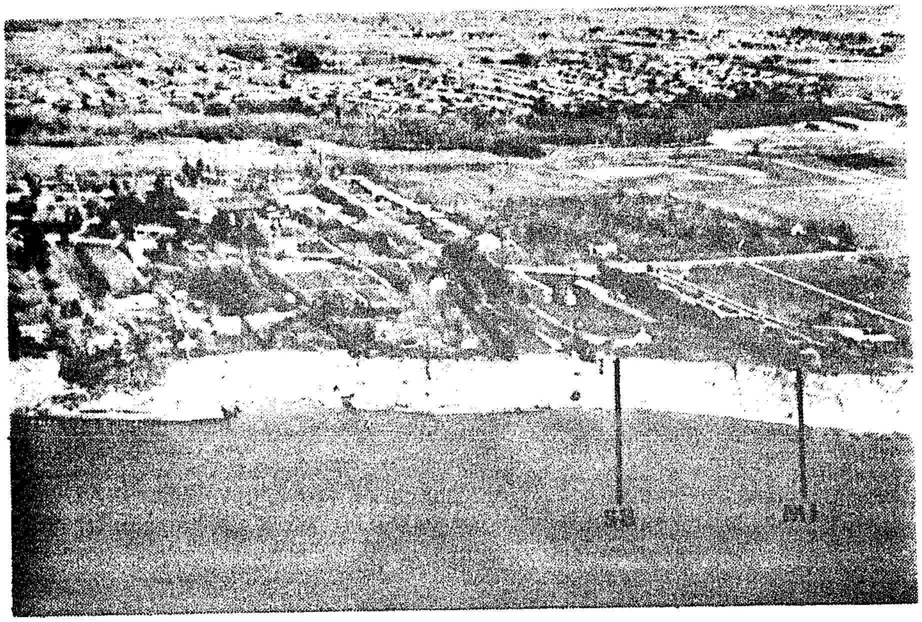


(A) April 24, 1969

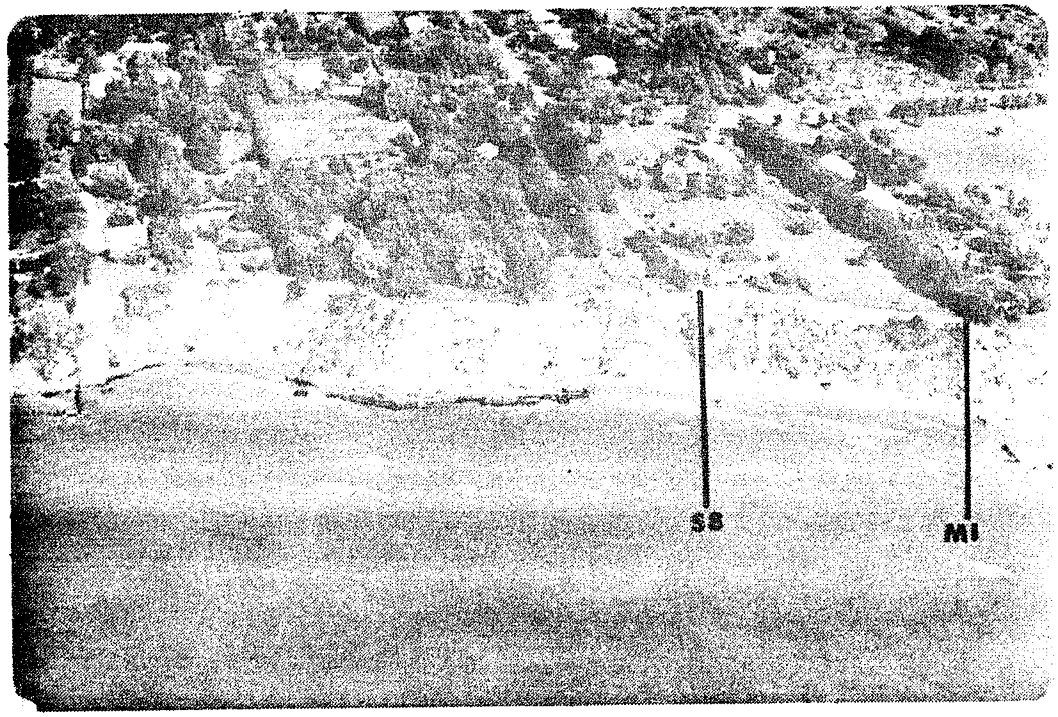


(B) March 27, 1973

Figure 17. Loss of homes due to accelerated bluff recession, 1969 to 1978. This location is in the South ½ / Section 4 / T5S,R19W, Shoreham, Berrien County, Michigan. Between September, 1967, and April, 1977, the bluff at site S8 receded 166.5 feet (17.29'/yr; 50.75 m or 5.27 m/yr). Long-term (1829-1977) retreat at site M1 is 278.13 feet (1.88'/yr; 84.77 m or 0.573 m/yr) and recent losses for four years (1973-1977) amount to 55.13 feet (13.78'/yr; 16.8 m or 4.2 m/yr); see Table 14.



(C) April or May, 1975



(D) August 29, 1978

Figure 17 (cont'd.).

reconstructed, and repaired by segments since the 1930's, the jetties reached their present lengths in 1903.[3] Prior to the 1830's most of the shorezone for several miles south of the St. Joseph River was apparently in a state of near equilibrium (Herbert, 1974). And until the first high water period (1916 to 1920) following the 1903 completion of the jetties the Shoreham bluffs experienced very little retreat. A Corps of Engineers' report (1958) reveals no recession at one site and a 23 foot loss[4] at another between 1830 and 1872. From an unpublished report, William J. Gibbs, Jr., of Shoreham writes:

> Being familiar, as a boy in 1916, with the beach and bluff along Lake Michigan from the harbor at St. Joseph, south to the south end of the Grand Mere area (10 to 12 miles), and having seen the lush growth and high trees on top of, and on the bluff [slope], and the several old wagon trails down the bluff to the beach--these trails lined with 75 to 100 foot high white pines--I am convinced that there had been no serious erosion of the bluff in this area for many years prior to 1916, and as far back as 1872.

Before 1903, but subsequent to the 1830's, some sand was probably bypassing the jetties and reaching downdrift beaches. But in 1903 a critical length may have been reached with the final extension whereby the structures cut completely across the littoral zone and essentially blocked all sand movement to the south. Bluff erosion was not an immediate problem because lake levels were low and beaches wide. However, with the onset of high water elevations in 1916 bluff recession

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[3] Following the 1903 additions of 1,002 (north) and 1,802 (south) feet, the jetties reached their present lengths of 3,152 (north) and 3,931 (south) feet.

[4] The survey line for this measurement was not taken perpendicular to the bluff crest but was run along a north-south section line intersecting the crest at an acute angle; consequently, actual retreat would be less than this 23 feet.

became a concern at some locations south of the jetties. Sites closer to these harbor structures were first to experience appreciable losses. In 1917 the City of St. Joseph found it necessary to install protective devices to preserve its water intake and pumping facilities. Although erosion apparently occurred along the Shoreham bluffs, accelerated retreat appeared limited to the St. Joseph shoreland during this period. But during all subsequent high water episodes the Shoreham bluffs experienced significant recession.

Bluff Recession: 1938 to 1977

The 15 Shoreham sites analyzed in detail are shown in Figure 18 and their recession rates are listed in Table 11. For 12 of the 15 locations recent (1967 to 1977) mean yearly retreat values are higher than for the periods 1938 to 1967 and 1938 to 1977. But two places (S12 and S13) underwent lower average rates between 1967 and 1977 than during the other time spans, whereas only one site (S14) displayed no bluff recession between 1938 and 1977. Furthermore, mean annual recession values for 12 of 15 points were lower between 1938 and 1967 than between 1938 and 1977.

The marked difference in average annual retreat rates for the three time intervals illustrates the importance of "period of record" with regard to recession rate data. Generally higher recession values are recorded for periods containing greater percentages of years when water levels are above normal. Between 1967 and 1977 Lake Michigan was above its modern long-term (1900-1977) mean annual elevation just over 80% of the time, and yearly retreat values for the 15 sites averaged a relatively high 6.80 feet (2.073 m). However, when calculated for the period 1938 to 1967, the same sites lost an average of 1.72 feet

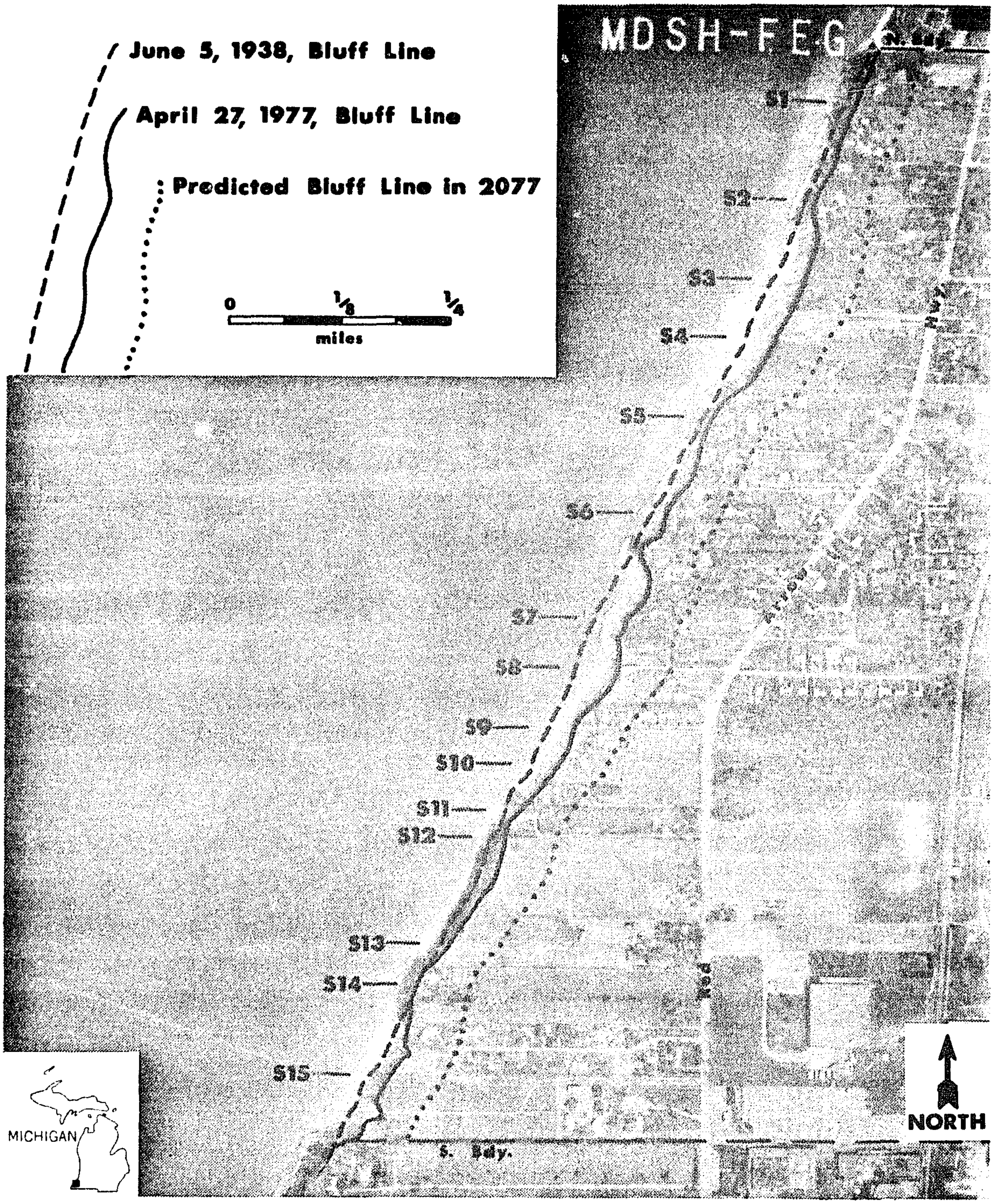


Figure 18. April, 1977, aerial photograph of the Shoreham, Berrien County, Michigan, case study area showing the 15 site locations, the June 5, 1938, and April 27, 1977, bluff lines, and the predicted bluff crest position in 2077. This area is located in Sections 3, 4, and 9 / T5S,R19W.

Table 11. Bluff recession rates at the Shoreham, Berrien County, Michigan case study sites, 1967 to 1977, 1938 to 1967, and 1938 to 1977.

Site No.	Bluff Recession 9/11/67-4/27/77	Average Annual Bluff Recession 9/11/67-4/27/77	Bluff Recession 6/5/38-9/11/67	Average Annual Bluff Recession 6/5/38-9/11/67	Bluff Recession 6/5/38-4/27/77	Average Annual Bluff Recession 6/5/38-4/27/77
S1	17.9 feet (5.46 m)	1.86 feet (0.567 m)	22.9 feet (6.98 m)	0.78 feet (0.238 m)	40.8 feet (12.44 m)	1.05 feet (0.320 m)
S2	59.7 feet (18.20 m)	6.20 feet (1.890 m)	1.5 feet (0.46 m)	0.05 feet (0.015 m)	61.2 feet (18.65 m)	1.57 feet (0.479 m)
S3	102.3 feet (31.18 m)	10.62 feet (3.237 m)	55.7 feet (16.98 m)	1.90 feet (0.579 m)	158.0 feet (48.16 m)	4.06 feet (1.237 m)
S4	96.9 feet (29.54 m)	10.06 feet (3.066 m)	81.5 feet (24.84 m)	2.78 feet (0.847 m)	178.4 feet (54.38 m)	4.59 feet (1.399 m)
S5	9.5 feet (2.90 m)	0.99 feet (0.302 m)	10.9 feet (3.32 m)	0.37 feet (0.113 m)	20.4 feet (6.22 m)	0.52 feet (0.158 m)
S6	65.3 feet (19.90 m)	6.78 feet (2.067 m)	11.2 feet (3.41 m)	0.38 feet (0.116 m)	76.5 feet (23.32 m)	1.96 feet (0.597 m)
S7	113.5 feet (34.59 m)	11.79 feet (3.594 m)	85.3 feet (26.00 m)	2.91 feet (0.887 m)	198.8 feet (60.59 m)	5.11 feet (1.558 m)
S8	166.5 feet (50.75 m)	17.29 feet (5.270 m)	93.4 feet (28.47 m)	3.19 feet (0.972 m)	259.9 feet (79.22 m)	6.68 feet (2.036 m)
S9	96.2 feet (29.32 m)	9.99 feet (3.045 m)	66.9 feet (20.39 m)	2.28 feet (0.695 m)	163.1 feet (49.71 m)	4.19 feet (1.277 m)

Table 11 (cont'd.).

Site No.	Bluff Recession 9/11/67-4/27/77	Average Annual Bluff Recession 9/11/67-4/27/77	Bluff Recession 6/5/38-9/11/67	Average Annual Bluff Recession 6/5/38-9/11/67	Bluff Recession 6/5/38-4/27/77	Average Annual Bluff Recession 6/5/38-4/27/77
S10	122.6 feet (37.37 m)	12.73 feet (3.880 m)	55.8 feet (17.01 m)	1.91 feet (0.582 m)	178.4 feet (54.38 m)	4.59 feet (1.399 m)
S11	46.9 feet (14.30 m)	4.87 feet (1.484 m)	65.2 feet (19.87 m)	2.23 feet (0.680 m)	112.1 feet (34.17 m)	2.88 feet (0.878 m)
S12	2.5 feet (0.76 m)	0.26 feet (0.079 m)	58.7 feet (17.89 m)	2.00 feet (0.610 m)	61.2 feet (18.65 m)	1.57 feet (0.479 m)
S13	11.1 feet (3.38 m)	1.15 feet (0.351 m)	55.2 feet (16.82 m)	1.89 feet (0.576 m)	66.3 feet (20.21 m)	1.70 feet (0.518 m)
S14	0.0 feet (0.00 m)	0.00 feet (0.000 m)	0.0 feet (0.00 m)	0.00 feet (0.000 m)	0.0 feet (0.00 m)	0.00 feet (0.000 m)
S15	70.8 feet (21.58 m)	7.35 feet (2.240 m)	92.3 feet (28.13 m)	3.15 feet (0.960 m)	163.1 feet (49.71 m)	4.19 feet (1.277 m)
MEAN	65.4 feet (19.93 m)	6.80 feet (2.073 m)	50.4 feet (15.36 m)	1.72 feet (0.524 m)	115.9 feet (35.33 m)	2.98 feet (0.908 m)

Table 11 (cont'd.).

Mean Average Annual Lake Level	Percent of Period When Average Annual Lake Level Was Above the Modern Long-Term (1900-1977) Mean
1967 to 1977: 578.49 feet	1967 to 1977: 81.8%
1938 to 1967: 577.93 feet	1938 to 1967: 40.0%
1938 to 1977: 578.10 feet	1938 to 1977: 52.5%

(0.524 m) yearly; and during this phase lake levels were above normal only 40% of the time. Between 1938 and 1977 levels were high about 50% of the time and yearly recession averaged 2.98 feet (0.908 m). Table 12 shows varying recession rates during different periods for site M1 (South Line / Section 4 / T5S,R19W, Figures 4 and 18) and may serve as another example of the relationship between average annual retreat values and the interval between measurements.

Examination of the aerial photography (Table 10) shows that in Shoreham the positions of shorezone protection structures greatly influence the variations in bluff crest recession. As is common elsewhere, there is a lack of uniform protection or even a coordinated effort by adjacent lot owners to protect the bluff. Consequently, erosion losses, at least on a short-term basis, may vary considerably from lot to lot depending on the absence or existence and effectiveness of protective structures (Table 11 and Figure 18). Bluff segments between such devices commonly experience rapid retreat during times of high water (Figure 19).

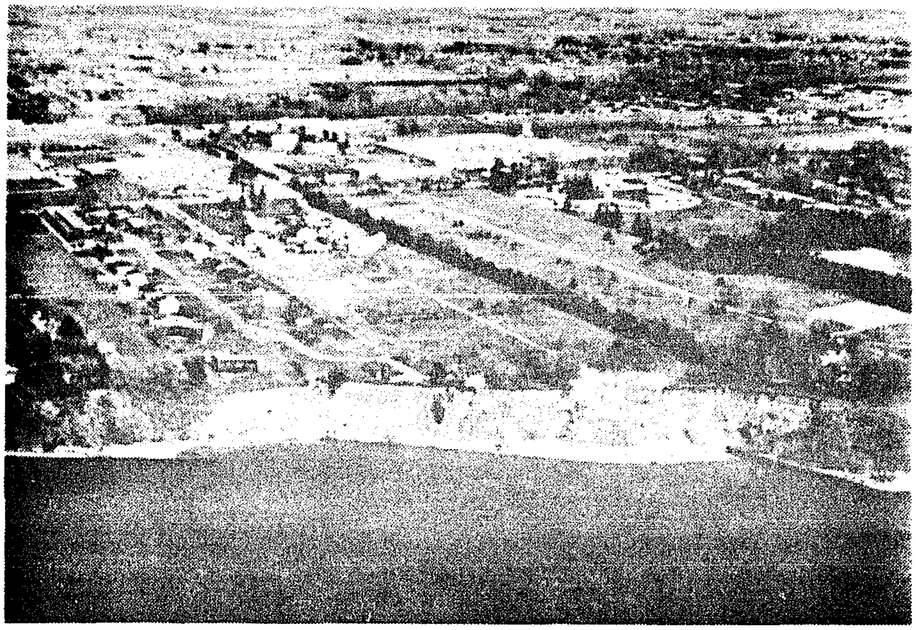
Only one structure built in the 1950's appears to be effective today (site S14, Table 11, and Figures 18 and 20) and many constructed during the last 10 years have already needed substantial reinforcement or have failed. Most seawalls and revetments are eventually breached and/or flanked by storm waves (Figure 21). Furthermore, aerial photos reveal that beaches did not develop in front of these structures even when relatively wide beaches develop nearby (Figures 19 and 20). And along Shoreham groins were found to be ineffective for protecting the bluff when lake levels remained high for several years. Even artificially constructed beaches designed to "feed" sand to downdrift shores proved

Table 12. Average annual bluff crest recession rates for various time periods at site M1, South Line / Section 4 / T5S,R19W, Shoreham, Berrien County, Michigan (see Figure 15).

Period	Average Annual Recession Rate	Source
1829 to 1977	1.88 feet (0.573 m)	this study
1829 to 1973	1.55 feet (0.472 m)	this author
1829 to 1957	1.11 feet (0.338 m)	Powers (1958)
1830[a] to 1872	+0.07 feet[b] (+0.021 m)	U.S. Army Corps of Engineers (1958)
1872 to 1950	1.28 feet (0.390 m)	U.S. Army Corps of Engineers (1958)
1950 to 1954	12.50 feet (3.810 m)	U.S. Army Corps of Engineers (1958)
1957 to 1973	5.06 feet (1.542 m)	this author
1957 to 1977	6.81 feet (2.076 m)	this author
1973 to 1977	13.78 feet (4.200 m)	this author

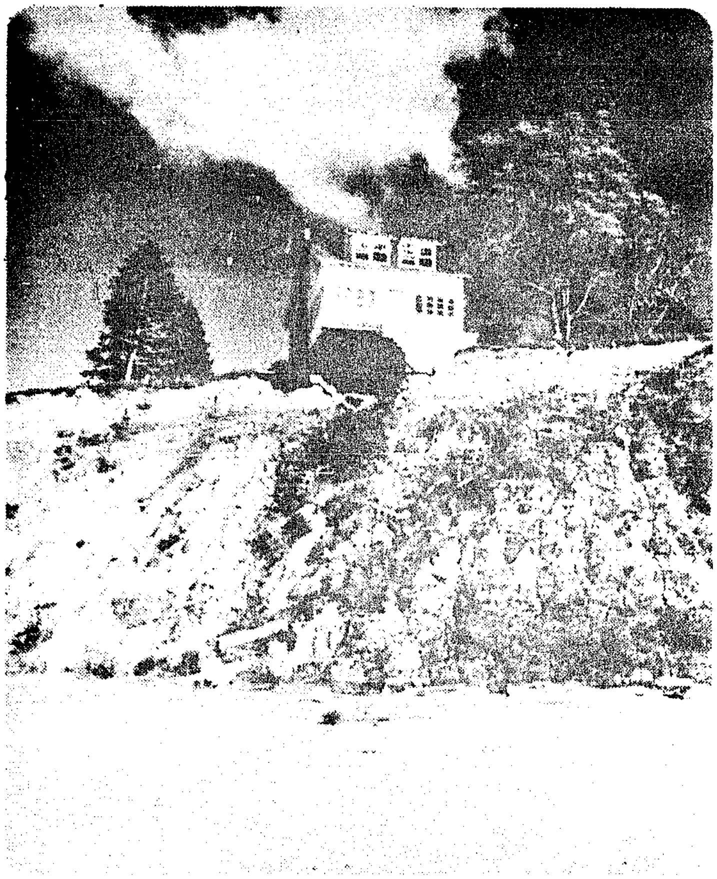
[a] This date should be 1829.

[b] This value should probably be zero as accretion of this bluff is not possible. The rate was determined by comparing a U.S. Lake Survey chart to the original General Land Office survey.

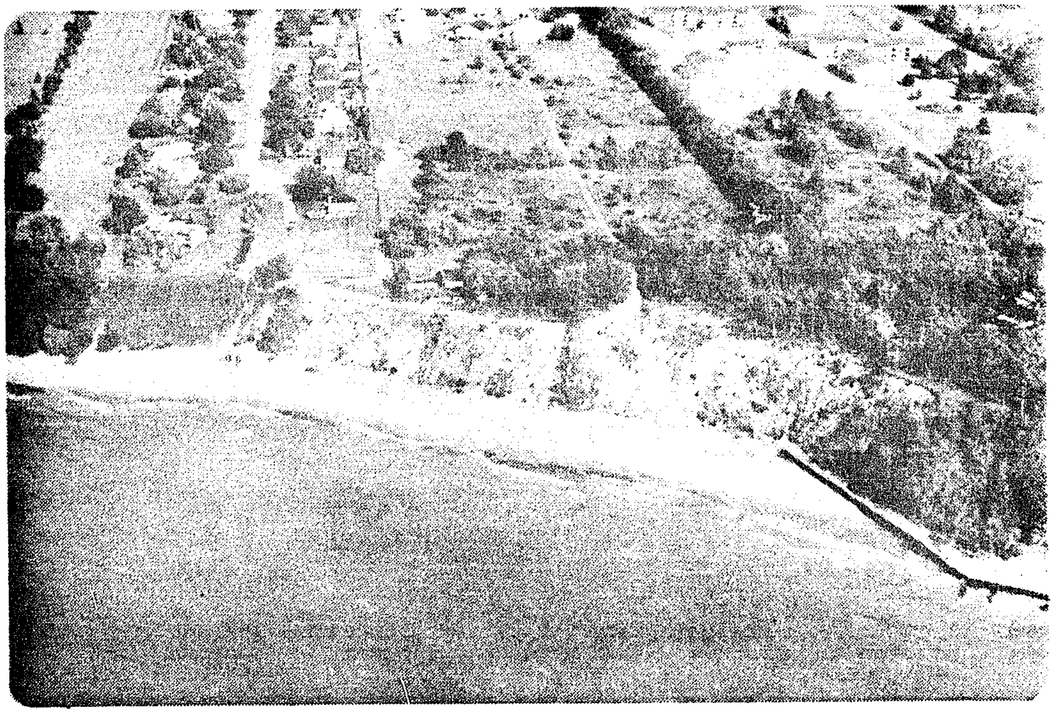


(A) April or May, 1975

Figure 19. House being lost due to accelerated bluff recession between two shorezone structures, 1975 to 1978. This location is at the Centerline / Section 9 / T5S,R19W, Shoreham, Berrien County, Michigan.



(B) August 24, 1977



(C) August 29, 1978

Figure 19 (cont'd.).

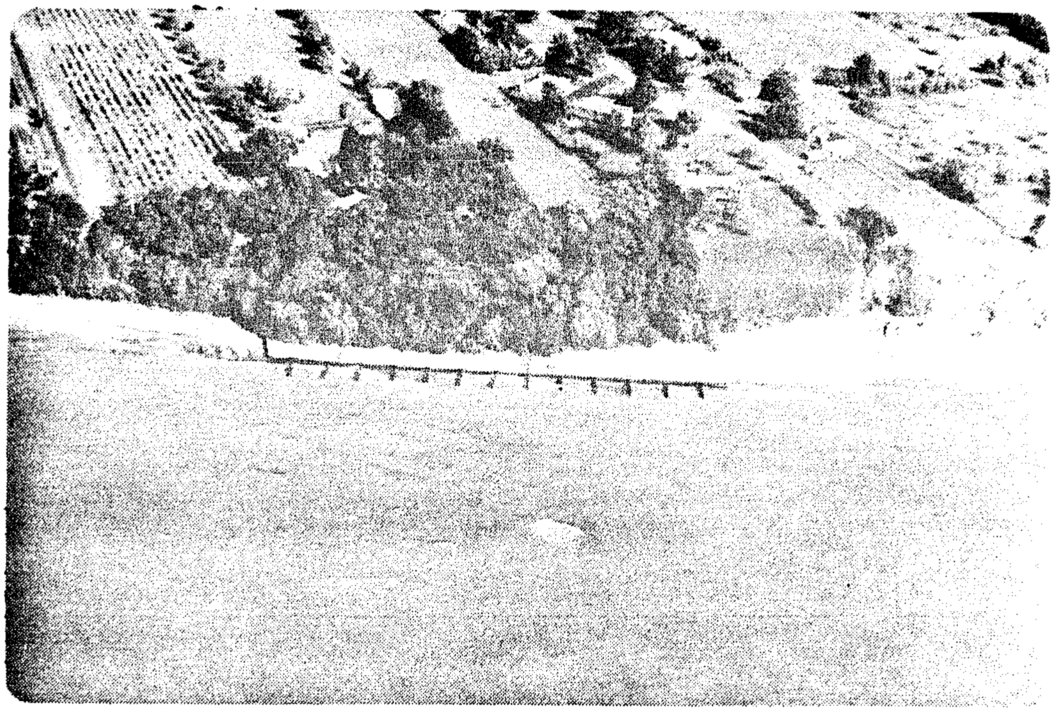
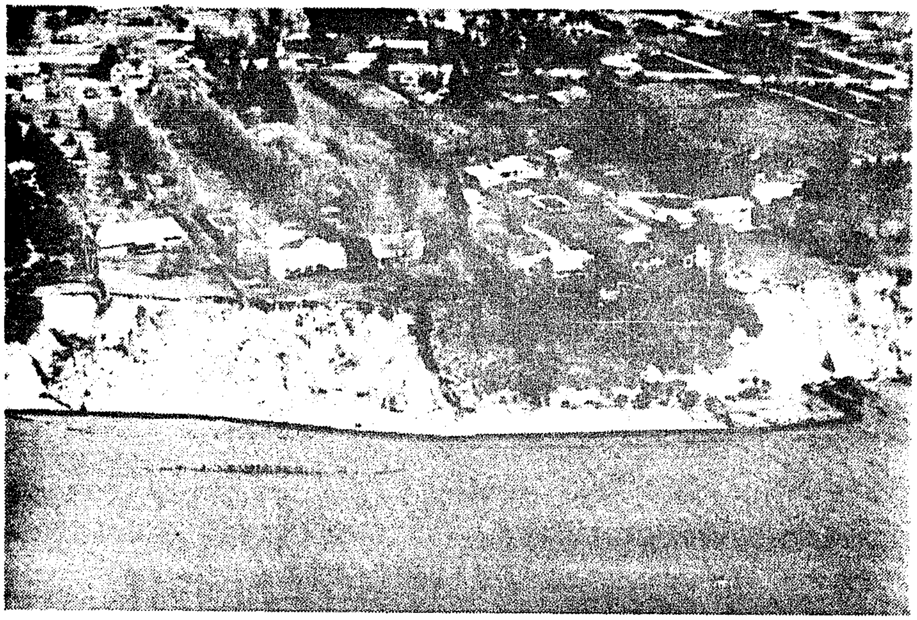
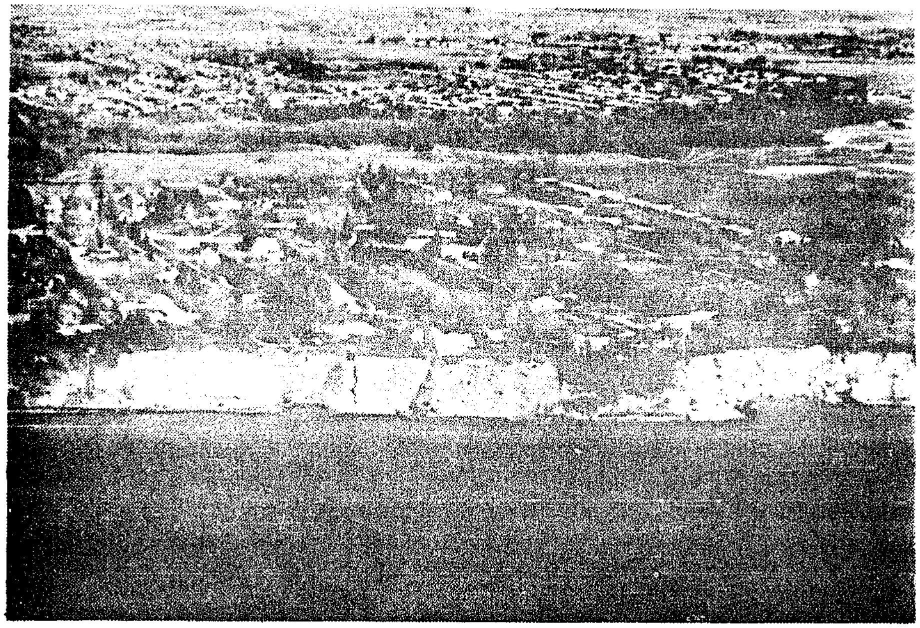


Figure 20. Site S14 (Table 13 and Figure 18) in the North ½ / Section 9 / T5S,R19W, Shoreham, Berrien County, Michigan. Constructed in the early 1950's this steel piling seawall and groin system has effectively protected this bluff segment. The area behind the structure is the only place in the case study reach that has not undergone retreat since 1938. This photo was taken on August 29, 1978.

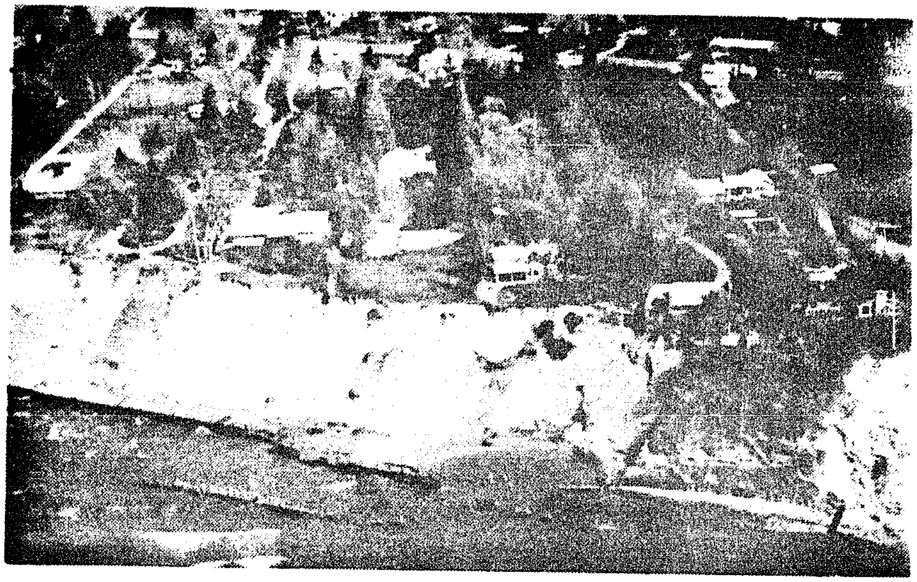


(A) March 27, 1973

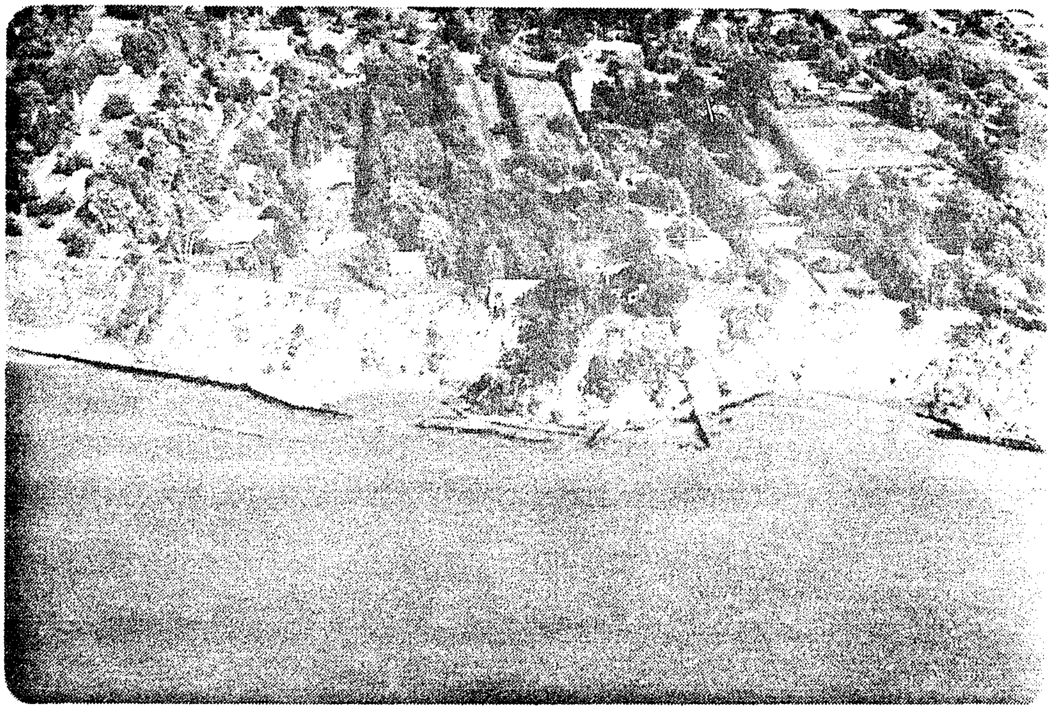


(B) April or May, 1975

Figure 21. Bluff recession and loss of a house following a breach in the seawall by storm waves, 1973 to 1978. The seawall has also been flanked. This lakeshore segment is located in the South ½ / Section 4 / T5S,R19W, Shoreham, Berrien County, Michigan.



(C) April, 1977



(D) August 29, 1978

Figure 21 (cont'd.).

unsatisfactory for preventing bluff losses; without continual sand supplement these feeder beaches are soon completely removed by shorezone processes (Figure 22).

The most apparent consequence of the disjunct and intermittant arrangement of shore protection structures is the evolution of much more irregular shore and bluff lines than would be expected if no or few structures existed. In 1938 no structures were visible on the photography[5] and the bluff line was essentially straight. But because of the installation of numerous protection devices in the 1950's, late 1960's, and during the 1970's, by 1977 the shoreline and bluff line had taken on an irregularly scalloped appearance (Figure 18).

The Northern Kenosha County Case Study

Characteristics

Historically northern Kenosha County has been subject to appreciable bluff recession. In 1870 Andrews cited bluff retreat of 12 feet (3.66 m) per year[6] at one location and Chamberlin (1877) reported losses averaging 1.87 feet (0.57 m) annually between 1836 and 1874 at the Kenosha-Racine county line. Lapham (1847) and Goldthwait (1907) discussed the effects of bluff retreat on sections immediately south of the study area. And during the early 1950's high rates of recession warranted initiation of erosion control studies (U.S. Army Corps of Engineers, 1953; 1955) in the region. The present investigation determined long-term (1835-36 to 1976) recession rates

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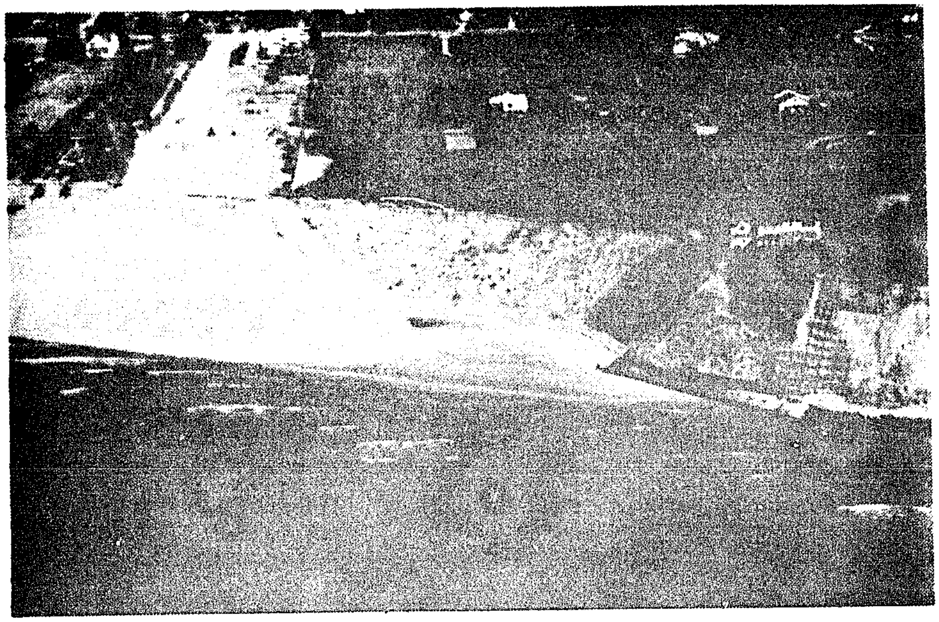
[5] It is possible that several structures may have been buried by beach sand.

[6] The rates cited by Andrews were for periods varying in length from 10 to 35 years.



(A) April, 1977

(B) August 29, 1978

Figure 22. Site of a feeder beach, 1977-1978. This type of artificial beach is designed to "feed" sand to downdrift shores so that beaches there may widen and protect the bluff from storm waves. This location (site S4, Table 13, Figure 18) is in the South ½ / Section 3 / T5S,R19W, Shoreham, Berrien County, Michigan.
(A) April 1977: The feeder beach is being built.
(B) August 29, 1978. Nothing remains of the feeder beach one year later.

for sites at the southern and northern boundaries and at the center point of the case study segment. These rates are:

Site W5	South Line / Sections 7 & 8 / T2N,R23E	2.74'/yr (0.835 m/yr)
Site W6	South Line / Section 5 / T2N,R23E	2.43'/yr (0.741 m/yr)
Site W7	South Line / Section 32 / T3N,R23E	2.44'/yr (0.744 m/yr)

Bare, steep bluffs, structural losses, and the large number of protective measures along the present shore indicate that bluff recession is still a major problem (Figure 23).

The bluffs in the area are 25 to 35 feet high. At the county line a clay loam till forms the lower three-quarters of the bluff profile with lacustrine sediments on top. Southward, however, the lacustrine/till contact descends to near and below lake level, with a corresponding thickening of the overlying lacustrine sediments (Table 13). In the more permeable layers ground water seeps are common and contribute to bluff slope instability. Little beach-building material is contained in the bluffs and only a small quantity of such material is supplied by littoral drift from the north[7] (U.S. Army Corps of Engineers, 1955). At the time of the investigation beaches varied in width from zero to 35 feet. Although trending generally N15^{o}E, the shoreline is slightly concave and includes several smaller undulations. These irregularities have persisted at least since 1941 and may have been initiated by the non-uniform placement of groins (which are numerous on the 1941 photos) along the shore. The largest waves affecting the area are generated by winds from the northeast quadrant; to the north-northeast fetch is 260 miles, to the east, 80 miles, and to the southeast, 75 miles.

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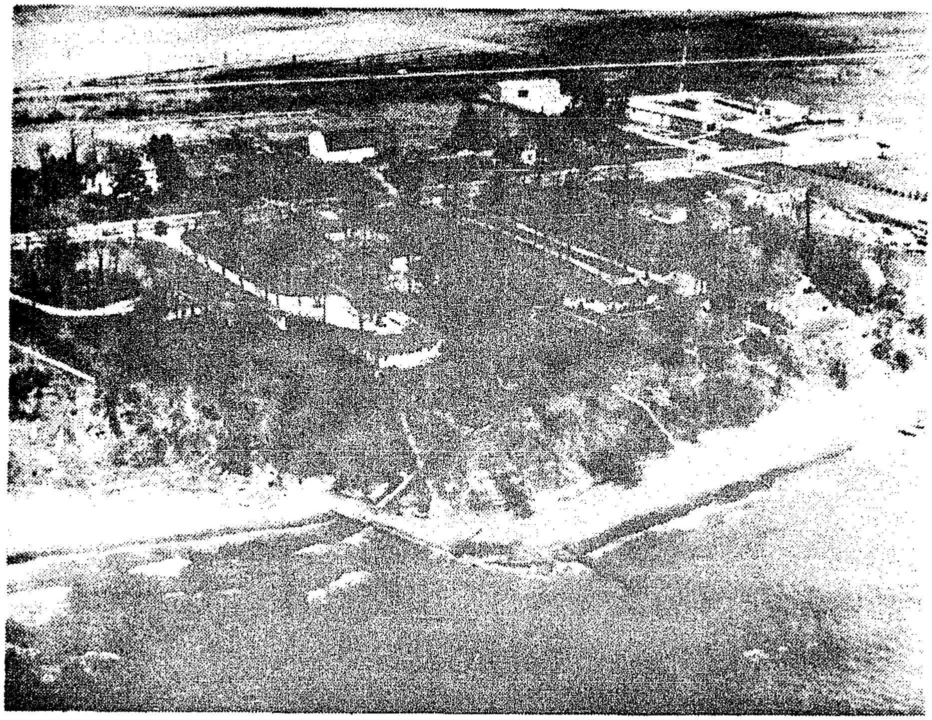
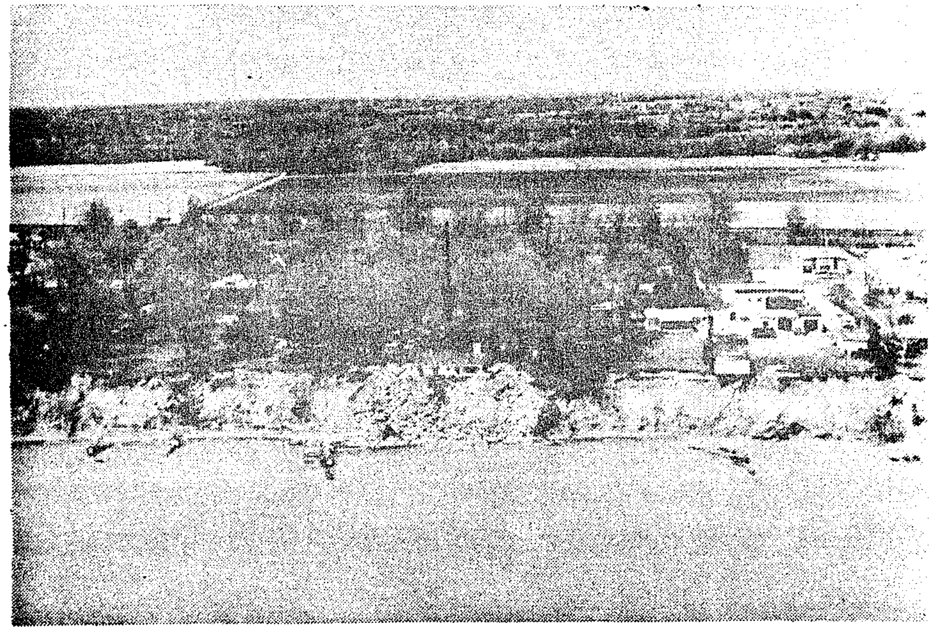
[7] Predominant littoral drift is north to south. "Since the construction of the groin system along the southern frontage of Racine County in 1922, the volume of beach-building material available for littoral movement into Kenosha County probably does not exceed 1,000 cubic yards annually" (U.S. Army Corps of Engineers, 1955, p. 13).



(A) 1959



(B) May 19, 1976

Figure 23. Bluff recession in the North ½ / Section 5 / T2N,R23E, Kenosha County, Wisconsin, 1959 to 1976. If it were not for fill dumped over the bluff edge the house (arrow) in the 1959 photo (A) would have been destroyed by 1976 (photo B). At location K4 (Table 16 and Figure 24) average bluff recession between 1969 and 1975 was 3.92 feet per year (1.195 m/yr), and from 1941 to 1975, 1.50 feet per annum (0.457 m/yr).

Table 13. Selected bluff profiles in the northern Kenosha County case study area.

South Line/ Sections 7 & 8/ T2N,R23E		South Line/ Section 5/ T2N,R23E		Kenosha-Racine Co. Line South Line/ Section 23/ T3N,R23E
Profile 5	Profile 4	Profile 3	Profile 2	Profile 1
Profile 5	Profile 4	Profile 3	Profile 2	Profile 1
4½' - Sand 28½' - Silty Clay with silt & silt loam zones in lower part	5' - Sand 27½' - Silty Clay with silt & silt loam zones in lower part	6½' - Sand with pebbles 10½' - Silty Clay 6½' - Covered 4' - Silty Clay 4' - Clay Loam with pebbles & cobbles (Till)	4½' - Sand with pebbles in lower part 8' - Silty Clay 12½' - Covered 5' - Clay Loam with pebbles & cobbles (Till)	8' - Complex Lacustrine Sequence; interbedded zones of sand, silty loam, loam, & sandy loam 22' - Clay Loam with pebbles & cobbles (Till)

Bluff Recession: 1941 to 1975

For six years (1969 to 1975) within the present period of high lake levels 15 of 22 Kenosha County sites experienced higher average annual recession rates than they did between either 1941 and 1969 or 1941 and 1975; mean retreat at two locations was less (Figure 24 and Table 14). Bluff lines at the other five points have remained stable since 1941. In addition, 15 sites sustained lower average annual retreat between 1941 and 1969 than during the time 1941 to 1975. As a whole, the study area's mean recession rate for each of the three periods is:

1969 to 1975	2.11 feet/year (0.643 m/yr)
1941 to 1969	0.84 feet/year (0.256 m/yr)
1941 to 1975	1.04 feet/year (0.317 m/yr)

Although overall retreat rates are notably less, the pattern of these rates with respect to the three periods of record is similar to that of the Shoreham lakeside (Tables 11 and 14). The values differ depending on the period measured and the proportion of years within each time span when water levels are above average. The mean annual lake elevation was above the average each year between 1969 and 1975, and annual bluff line losses were the greatest during this period. Of the three intervals, average annual losses were least between 1941 and 1969, the period corresponding to the lowest percentage of years with high lake levels.

Within each time interval bluffs at individual sites receded at varying rates, and generally those in the southern section less rapidly than those to the north. Based on visual examination of vertical and oblique aerial photographs the point-to-point differences appear not only related to the spatial arrangement of protection devices along the shore

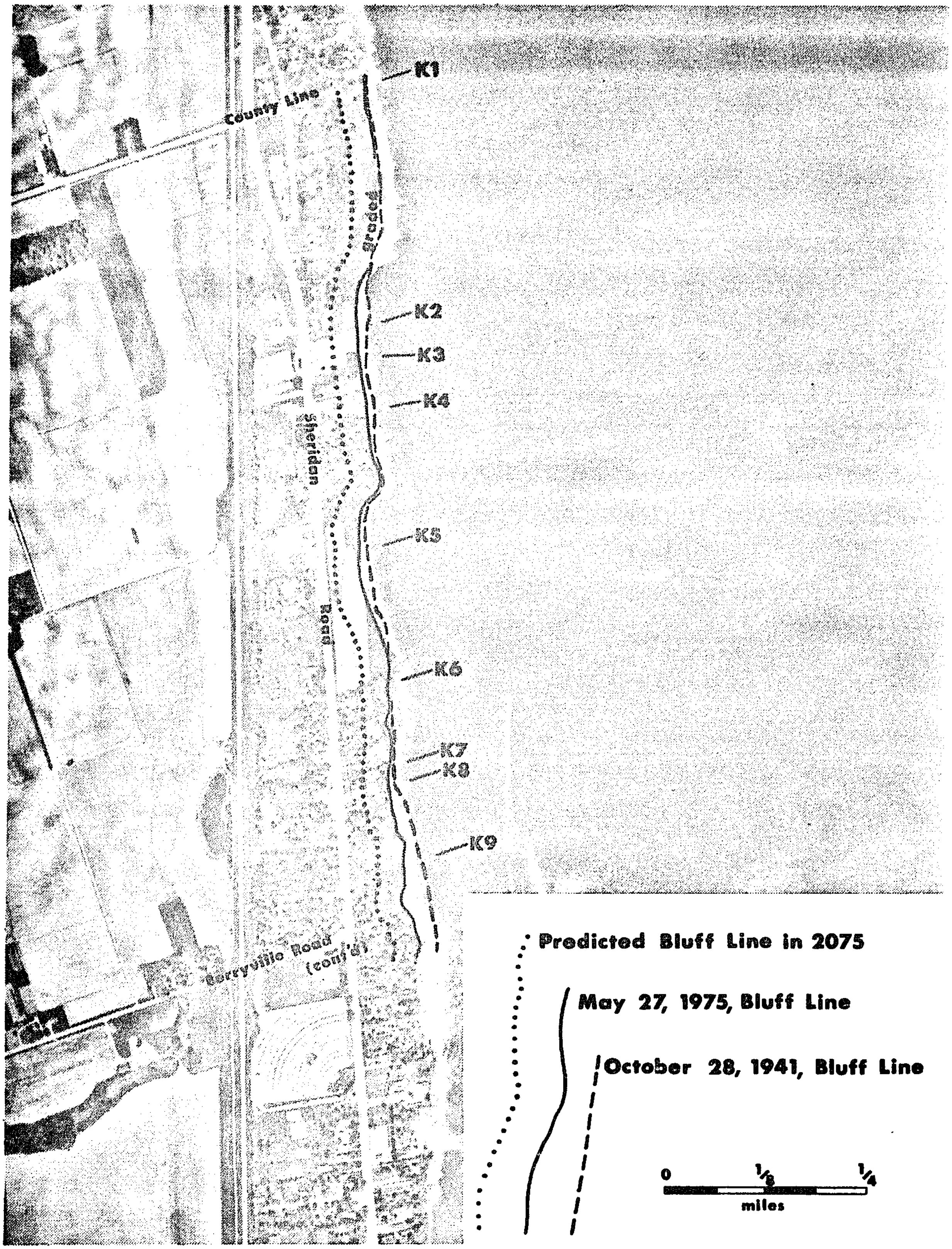


Figure 24. May, 1975, aerial photograph of the northern Kenosha County, Wisconsin, case study area showing the 22 site locations, the October 28, 1941, and May 27, 1975, bluff lines, and the predicted bluff crest position in 2075. This area is located in Sections 5, 7, and 8 / T2N,R23E.

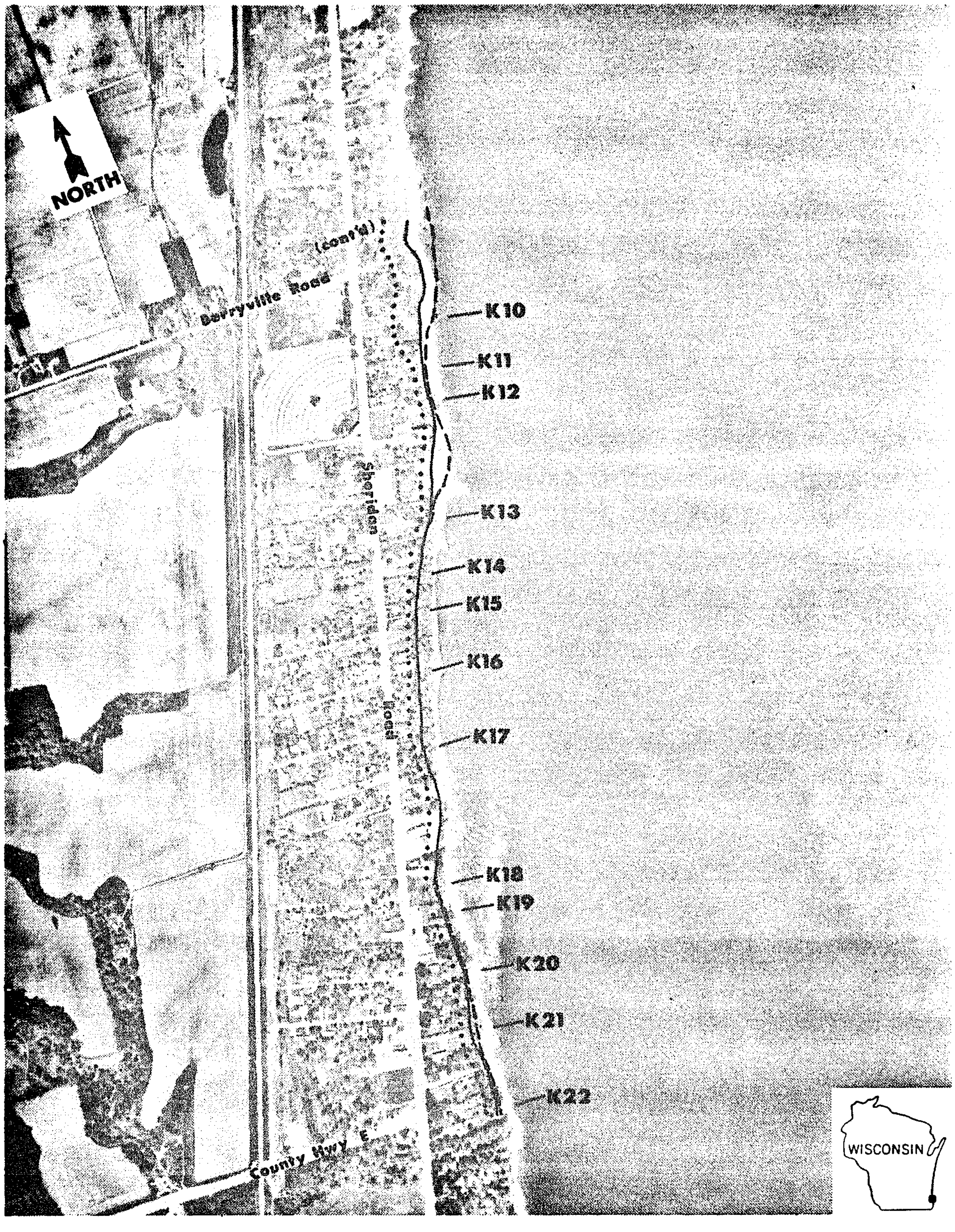


Figure 24 (cont'd.).

Table 14. Bluff recession rates at the northern Kenosha County, Wisconsin case study sites, 1969 to 1975, 1941 to 1969, and 1941 to 1975.

Site No.	Bluff Recession 6/28/69-5/27/75	Average Annual Bluff Recession 6/28/69-5/27/75	Bluff Recession 10/28/41-6/28/69	Average Annual Bluff Recession 10/28/41-6/28/69	Bluff Recession 10/28/41-5/27/75	Average Annual Bluff Recession 10/28/41-5/27/75
K1 (W7)	3.6 feet (0.33 m)	0.61 feet (0.186 m)	11.5 feet (3.51 m)	0.42 feet (0.128 m)	15.1 feet (4.60 m)	0.45 feet (0.137 m)
K2	39.8 feet (12.13 m)	6.72 feet (2.048 m)	55.9 feet (17.04 m)	2.02 feet (0.616 m)	95.7 feet (29.17 m)	2.85 feet (0.869 m)
K3	19.9 feet (6.07 m)	3.36 feet (1.024 m)	40.6 feet (12.37 m)	1.47 feet (0.448 m)	60.5 feet (18.44 m)	1.80 feet (0.549 m)
K4	23.2 feet (7.07 m)	3.92 feet (1.195 m)	27.2 feet (8.29 m)	0.98 feet (0.299 m)	50.4 feet (15.36 m)	1.50 feet (0.457 m)
K5	30.0 feet (9.14 m)	5.06 feet (1.542 m)	25.4 feet (7.74 m)	0.92 feet (0.280 m)	55.4 feet (16.89 m)	1.65 feet (0.503 m)
K6	0.0 feet (0.00 m)	0.00 feet (0.000 m)	0.0 feet (0.00 m)	0.00 feet (0.000 m)	0.0 feet (0.00 m)	0.00 feet (0.000 m)
K7	9.2 feet (2.80 m)	1.56 feet (0.475 m)	27.0 feet (8.23 m)	0.76 feet (0.232 m)	30.2 feet (9.20 m)	0.90 feet (0.274 m)
K8	12.7 feet (3.87 m)	2.15 feet (0.655 m)	37.7 feet (11.49 m)	1.36 feet (0.415 m)	50.4 feet (15.36 m)	1.50 feet (0.457 m)
K9	5.4 feet (1.65 m)	0.91 feet (0.277 m)	123.1 feet (37.52 m)	4.45 feet (1.356 m)	117.7 feet (35.87 m)	3.51 feet (1.070 m)

Table 14 (cont'd.).

Site No.	Bluff Recession 6/28/69-5/27/75	Average Annual Bluff Recession 6/28/69-5/27/75	Bluff Recession 10/28/41-6/28/69	Average Annual Bluff Recession 10/28/41-6/28/69	Bluff Recession 10/28/41-5/27/75	Average Annual Bluff Recession 10/28/41-5/27/75
K10	48.3 feet (14.72 m)	8.16 feet (2.487 m)	44.4 feet (13.53 m)	1.60 feet (0.488 m)	92.7 feet (28.25 m)	2.76 feet (0.841 m)
K11	7.7 feet (2.35 m)	1.30 feet (0.396 m)	12.3 feet (3.75 m)	0.44 feet (0.134 m)	20.0 feet (6.10 m)	0.60 feet (0.183 m)
K12	9.4 feet (2.87 m)	1.59 feet (0.484 m)	10.6 feet (3.23 m)	0.38 feet (0.116 m)	20.0 feet (6.10 m)	0.60 feet (0.183 m)
K13	13.3 feet (4.05 m)	2.24 feet (0.683 m)	6.7 feet (2.04 m)	0.24 feet (0.073 m)	20.0 feet (6.10 m)	0.60 feet (0.183 m)
K14	0.0 feet (0.00 m)	0.00 feet (0.000 m)	0.0 feet (0.00 m)	0.00 feet (0.000 m)	0.0 feet (0.00 m)	0.00 feet (0.000 m)
K15	0.0 feet (0.00 m)	0.00 feet (0.000 m)	0.0 feet (0.00 m)	0.00 feet (0.000 m)	0.0 feet (0.00 m)	0.00 feet (0.000 m)
K16	0.0 feet (0.00 m)	0.00 feet (0.000 m)	0.0 feet (0.00 m)	0.00 feet (0.000 m)	0.0 feet (0.00 m)	0.00 feet (0.000 m)
K17	0.0 feet (0.00 m)	0.00 feet (0.000 m)	0.0 feet (0.00 m)	0.00 feet (0.000 m)	0.0 feet (0.00 m)	0.00 feet (0.000 m)
K18	5.8 feet (1.77 m)	0.98 feet (0.299 m)	11.7 feet (3.57 m)	0.42 feet (0.128 m)	17.5 feet (5.33 m)	0.52 feet (0.158 m)

Table 14 (cont'd.).

Site No.	Bluff Recession 6/28/69-5/27/75	Average Annual Bluff Recession 6/28/69-5/27/75	Bluff Recession 10/28/41-6/28/69	Average Annual Bluff Recession 10/28/41-6/28/69	Bluff Recession 10/28/41-5/27/75	Average Annual Bluff Recession 10/28/41-5/27/75
K19	5.5 feet (1.68 m)	0.92 feet (0.280 m)	7.0 feet (2.13 m)	0.25 feet (0.076 m)	12.5 feet (3.81 m)	0.37 feet (0.113 m)
K20	15.0 feet (4.57 m)	2.53 feet (0.771 m)	7.5 feet (2.29 m)	0.27 feet (0.082 m)	22.5 feet (6.86 m)	0.67 feet (0.204 m)
K21	3.7 feet (1.13 m)	0.63 feet (0.192 m)	56.8 feet (17.31 m)	2.05 feet (0.625 m)	60.5 feet (18.44 m)	1.80 feet (0.549 m)
K22	21.5 feet (6.55 m)	3.63 feet (1.106 m)	6.1 feet (1.86 m)	0.22 feet (0.067 m)	27.6 feet (8.41 m)	0.82 feet (0.250 m)
MEAN	12.5 feet (3.81 m)	2.11 feet (0.643 m)	23.3 feet (7.10 m)	0.84 feet (0.256 m)	34.9 feet (10.64 m)	1.04 feet (0.317 m)

Mean Average Annual Lake Level

1969 to 1975: 579.65 feet
1941 to 1969: 578.05 feet
1941 to 1975: 578.34 feet

Percent of Period When Average Annual Lake Level Was Above the Modern Long-Term (1900-1977) Mean

1969 to 1975: 100 %
1941 to 1969: 44.8%
1941 to 1975: 54.3%

but also to variations in the natural processes operating in the nearshore environment. Groins, the most common protection structure in the area, have not prevented bluff retreat but recession rates are generally less severe where they exist. In some places where a series of groins occur the bluff edge has taken on a somewhat scalloped or serrated appearance (Figure 24). At site K6 (Table 14 and Figure 24) two groins, installed prior to 1941, have apparently eliminated bluff line retreat for the time being (Figure 25). And long-term (1835 to 1976) recession at the Kenosha-Racine county line (site W7 in the main study and K1 in the case study) is 343.8 feet (104.79 m), but between 1941 and 1975 losses only amounted to 15.1 feet (4.60 m); obviously, since before 1941, groins, and other subsequent structures, have been effective in greatly reducing bluff line retreat in this area.

Natural accretionary processes probably account for the stable bluff line positions at four adjacent sites (K14-K17, Figures 24 and 26) in the southern section of the study area. Situated in the lee of a small headland, a low but relatively broad beach terrace has fronted the bluff since at least 1937 (Figure 27). In 1941 the feature extended about 1,000 feet along the shore and reached a maximum width of approximately 200 feet. Typically undergoing erosion and narrowing during high lake stages, it widened at times of lower water levels, although its average width has grown progressively smaller. Goldthwait (1907) discussed a similar feature found about a mile farther south. He described the beach terrace as a cuspate foreland which probably built from littoral drift deposited in the quieter water back of a headland (Figure 28). Until now the beach terrace has prevented storm waves from reaching the bluff slope in the area under present investigation; unfortunately, these conditions may not last much longer. Recent high lake level storm

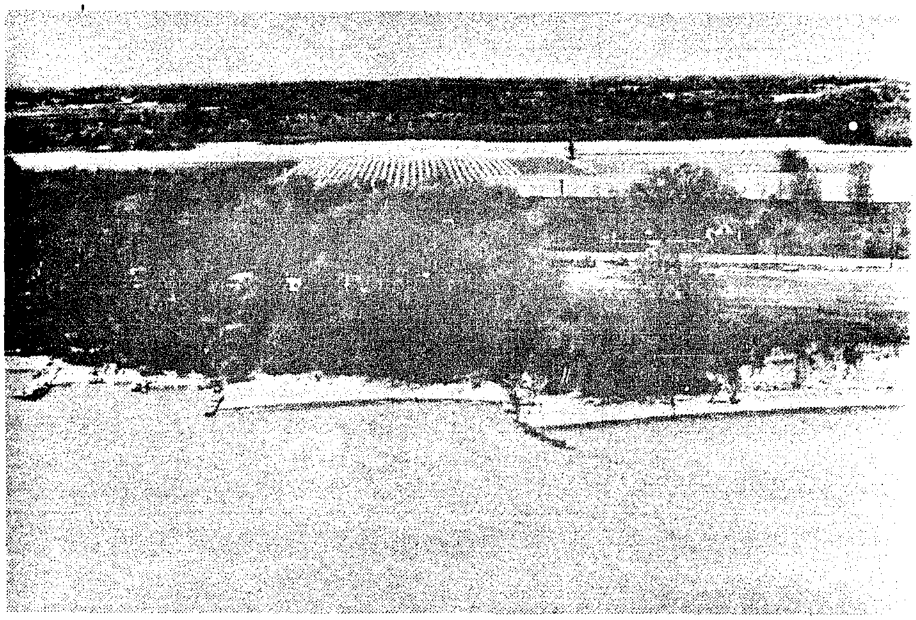


Figure 25. Site K6 in the South ½ / Section 5 / T2N,R23E, Kenosha County, Wisconsin. The two groins in the center of the photo, installed prior to 1941, have apparently so influenced shore conditions that no bluff line retreat has occurred since that date. This photo was taken on May 19, 1976.

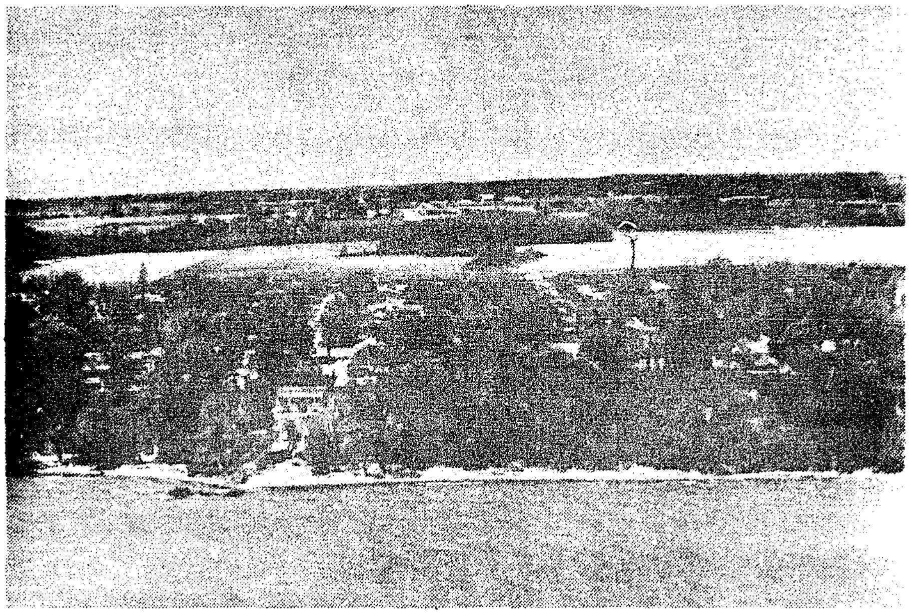
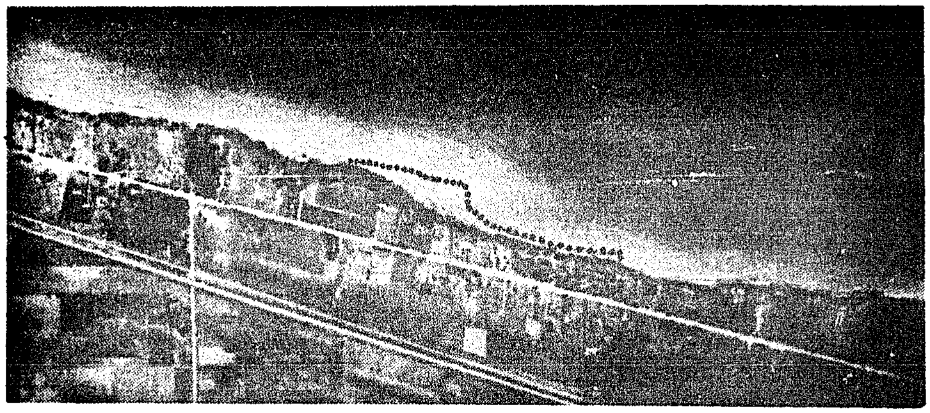
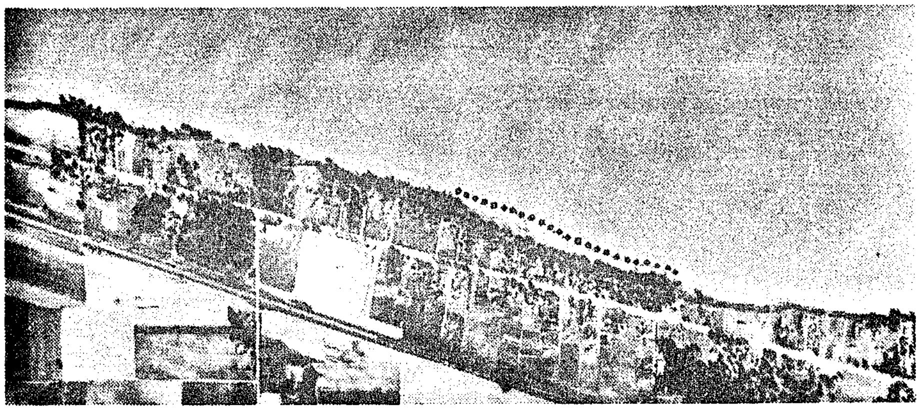


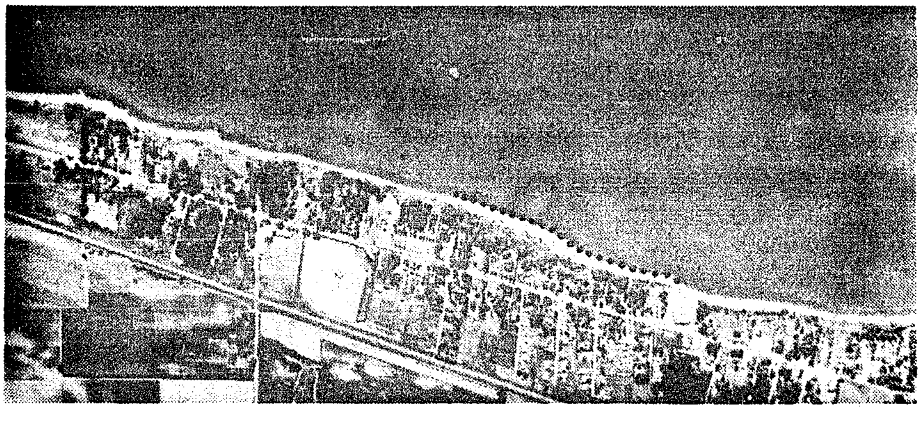
Figure 26. Generally protected against storm waves by a broad beach terrace, the bluff in this portion of Section 8 / T2N,R23W, Kenosha County, Wisconsin has undergone no crest recession since at least 1941. This photo was taken on May 19, 1976.



(A) August 12, 1937



(B) September 6, 1950



(C) June 24, 1963

Figure 27. Aerial photos taken in 1937, 1950, and 1963 showing the relatively broad beach terrace fronting the bluff segment encompassing sites K14-K17.

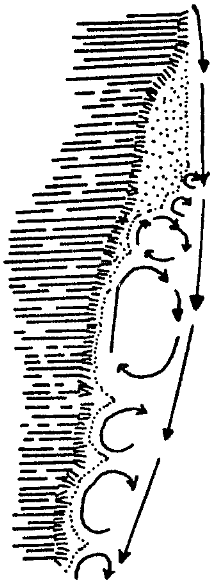


Figure 28. Goldthwait's (1907) sketch map of a cuspate foreland located about one mile south of the northern Kenosha County, Wisconsin, case study area, showing the supposed eddies in the shorezone current. This sketch is similar to the beach conditions which have existed along the shore fronting bluff sites K14-K17.

waves have eroded most of its breadth and part of the small headland to the north. Furthermore, a recently installed groin on its northern edge appears to interrupt the southward moving littoral drift supply to the beach.

Photographic and field data from the Kenosha and Shoreham case study areas demonstrate the dynamic nature of the Lake Michigan shorezone during the past four decades. Bluff recession is related to normal lakeshore processes and its rate at any point is influenced by local and regional environmental conditions and by shorezone protection structures. These artificial structures are typically ineffective in the long-term and are unattractive, potentially hazardous to shore users (Figures 29 and 30) and expensive. Based on previous and present events, bluff retreat may be expected to continue in the future.

Future Rates of Bluff Recession

Geomorphic processes have and will continue to modify the Lake Michigan margin. Wise use of any portion of the increasingly high value shoreland depends on an assessment of its vulnerability to future erosion. But severe limitations are placed on accurately forecasting this erosion because the variables influencing the erosion are many and their interrelationships are often not well understood. Nevertheless, this study provides a method of predicting future bluff crest positions which is applicable to the two case study areas. The procedure requires detailed knowledge of previous bluff recession rates for the area of interest and the historic record of mean monthly lake levels. From this data a representative bluff retreat value is determined which is then multiplied by a lake level factor to establish an estimate of the future bluff crest position.

Figure 29. Bluff protection measures in the North ½ / Section 8 / T2N,R23E, Kenosha County, Wisconsin. This photo was taken on July 30, 1978

Figure 30. Broken concrete slabs armoring the bluff slope in the South ½ / Section 8 / T2N,R23E, Kenosha County, Wisconsin. This photo was taken on July 30, 1978.

Methodology for Predicting Future Bluff Crest Positions

Period of Record and Data Base

The period of record on which future recession rates are based must be selected with care. As emphasized earlier (Tables 13, 14 and 16) average annual bluff line retreat may vary significantly depending on the interval between measurements. For example, mean recession rates for the Shoreham area are markedly higher between 1967 and 1977 than between 1938 and 1967, or 1938 and 1977. To predict the future crest line position based solely on the high rates of the present period would be misleading; this time span is noted not only for its high lake elevations but also for the persistency of those levels, a condition which is singular to this century. An adequate data base period preferably should encompass at least two stages of lower, and two episodes of higher, lake elevations. Thus, total bluff recession and the derived mean yearly retreat rate would reflect periods characterized by both low and high recession values.

For a given bluff segment it is also necessary for predictions of future bluff line positions to be based to a considerable extent on recession data from a modern period of record. Retreat rates derived from comparison of modern bluff lines to crests at the time of the original land surveys alone are inadequate for local predictions because potential data sites are too widely spaced for meaningful assessments to be made. More appropriate is to use older aerial photography as a base from which rates at numerous points within short distances can be determined by comparing the photos with recent imagery. Photography is generally available for the Lake Michigan shorezone since the late 1930's and early 1940's and since that period three low and three high lake stages have occurred. Furthermore, modern rates of retreat better reflect the influence of shorezone protection structures whose numbers have increased substantially during the last 30 years.

Representative Bluff Retreat Value for the Period of Record

For each shoreline mile it is generally accepted that a minimum of four (Martin Jannereth,[7] personal communication) or five (Stafford, 1971; Tanner, 1978) measurements at similarly spaced sites over an adequate period of time is necessary to establish a representative recession value. For those lakeshore reaches where sample sites have similar recession rates, a singular representative value may be established by computing the mean value of the individual sites. A more difficult problem arises where recessional losses of adjacent or nearby sites within a zone vary considerably, as they commonly do where shore protection structures exist or have existed during the period of record. In such cases extreme individual site values can greatly influence the mean and lead to erroneous conclusions (Blalock, 1972). A more reliable indicator may be to rank the individual values and to use the median figure as the rate most "typical" or representative (Blalock, 1972) of the lakeshore segment. Individual site values should be examined for consistency before establishing a median retreat rate. It may be advantageous to divide the length into two or more zones, each being assigned a different median value. This may occur if overall site values significantly change from one shoreline reach to another. However, segments would not be divided if adjacent sites repeatedly display

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[7] Mr. Jannereth is responsible for the Michigan Department of Natural Resources' program to determine bluff recession rates along the state's Great Lakes shorezone.

significantly different values, as they may do where shore protection structures partially protect the bluff.

Because of the point-to-point variability of bluff retreat values, in this study the median retreat value (ascertained from all available recession rates within the zone of interest) is considered a more meaningful and representative figure in the prediction procedure than the mean value. In areas incorporating sites with similar recessional rates the median would be very close to the mean but in those reaches where individual losses vary considerably the median figure may not be similar (Blalock, 1972).

Lake Level Factor and Prediction of Future Bluff Retreat

Berg and Collinson (1976) found that bluff erosion from wave attack in Illinois becomes significant when water elevations rise above 579 feet. Although at some places bluff retreat may occur below that level, and at others erosion may not happen until the lake is well above that measure, overall, Berg and Collinson's estimate seems reasonable for the case study areas. If the 579 foot level is a threshold above which most bluff line losses occur the duration of time when the lake is above this mark becomes especially significant.

In most studies estimating future bluff crest locations, the positions are established by multiplying the average annual bluff retreat value derived from the period of record for the particular lakeside segments by the number of years into the future the investigators wished to forecast. As long as the period of record spanned at least a high and low lake level interval the specific number of months or percentage of time when the levels were actually high during the period was given little attention. If long-term predictions are to be reasonable this factor must be considered.

Two assumptions are made in order to incorporate a future lake level factor in the prediction procedure: (1) The historic record of lake levels is a valid indicator of future conditions. For example, during the next hundred years lake levels can be expected to be above the 579 foot mark a length of time similar to the amount it was during the previous one hundred years. And (2), during the period of record (from which recessional values are established for a particular shore segment) significant bluff line losses occurred only during those months when the lake was above the 579 foot elevation.

On this basis a future retreat value, incorporating a lake level factor, can be devised for a shorezone segment by:

(1) Determining the number of months within the period of record (from which retreat values are derived) when water elevations were above 579 feet.

(2) Dividing the median retreat value for the period of record by the number of months established in (1).

(3) Selecting the future reference date and determining the number of years (X) between then and the end of the period of record.

(4) Determining the number of months during the prediction period when, based on historic lake level readings for X years, the lake could be expected to be above the 579 foot level.

(5) Multiplying the average monthly recessional value, derived in (2), by the number of months the lake is expected to surpass the 579 foot elevation, derived in (4).

Thus, based on known recession data from a previous period, an average monthly retreat value is assigned only to those months when Lake Michigan's elevation is above 579 feet. This figure then becomes the projected monthly rate of retreat during each month in the future when the lake's average height is expected to raise above 579 feet; below this level bluff recession is not anticipated. For example:

Problem: Predict the amount of bluff line retreat that will take place along a one mile shoreland segment during the next one hundred years.

Established:

(1) Twelve sample sites for which the median retreat value for a 35 year period of record is 70 feet (2.00'/yr).

(2) The lake level was above 579 feet for 120 months during the 35 year period of record.

If bluff recession only occurred during months when the mean lake level was above 579 feet, the average rate of retreat during each of these months would then be:

$$\frac{70'}{120 \text{ months}} = 0.583'/\text{month}$$

(3) For one hundred years prior to the end of the period of record, the mean monthly water elevation was above the 579 foot mark during 360 months.

Predicted Future Retreat: 0.583'/month x 360 months = <u>209.9 feet</u>

Bluff Crest Positions In the Next Century
Two Case Study Predictions

Shoreham

Bluff retreat was determined at 15 sites in Shoreham for the period of record June 5, 1938 to April 27, 1977 (Table 13). Median retreat for the area was 112.1 feet (2.88'/yr; 34.17 m or 0.878 m/yr).[8] During this time Lake Michigan's level was above 579 feet for 141 of the 467 months. And for all months during the 100 years prior to April, 1977, this same mean monthly level was exceeded on 413 occasions. Dividing 112.1 feet by 141 months, and multiplying the resulting quotient by 413 months, a retreat of 328.3 (100.13 m) is anticipated during the next century along the Shoreham bluffs (Figure 18).

At only one site (M1) in the area is a long-term recession value available and the anticipated rate of retreat (3.29'/yr or 1.003 m/yr) is substantially greater than the rate experienced by the measured site (1.88'/yr or 0.573 m/yr between 1829 and 1977). Apparently the higher anticipated rate reflects the rapid increase in bluff recession during the last four decades due largely to the adverse effects created by the St. Joseph harbor jetties and other shore protection structures. The 1.88'/yr (0.573 m/yr) retreat value for site M1, however, encompasses a large time span in the 1800's and early 1900's when the bluff line was unaffected by structures and remained relatively stable (Table 14).

Under present conditions bluff recession during the next 100 years may be expected to cause the destruction of no fewer than 33 homes, nine other buildings, three swimming pools, and a tennis court.

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[9] Mean retreat for the 10 sites is 52.8 feet (1.57'/yr; 16.09 m or 0.479 m/yr).

Furthermore, the irregularity of the bluff line will likely continue, and may increase, but because of the temporal and disjunct nature of shore protection structures it is not possible to predict a specific bluff line pattern.

Northern Kenosha County

In Kenosha County modern recession rates were based on the period of record October 28, 1941 to May 27, 1975 (Table 16). During this time bluffs along the northern and southern portions of the study area receded at significantly dissimilar rates. Therefore, a different representative bluff retreat value was established for each segment. Median retreat for the northern bluff line, corresponding to sites K1 through K10, was 50.4 feet (1.50'/yr; 15.36 m or 0.457 m/yr).[9] Median recession for the southern segment, coinciding with sites K11 through K22, was 20 feet (0.60'/yr; 6.10 m or 0.183 m/yr).[10] The bluff line along the northern stretch can be expected only to be about 167.9 feet[11] (51.15 m) inland from its present position in one hundred years. At that time the southern crest line is expected only to have receded 66.6 feet[12] (20.30 m) (Figure 24). The difference in bluff retreat between the northern and southern segments nicely illustrates the variability of recession along the Lake Michigan shoreline. If these variable conditions are widespread it is important

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[9] Mean retreat for the 10 sites is 52.8 feet (1.57'/yr; 16.09 m or 0.479 m/yr).

[10] Mean retreat for the 12 sites is 21.2 feet (0.67'/yr; 6.46 m or 0.204 m/yr).

[11] The value of 167.9 feet is the result of dividing 50.4 feet by 124 months, and multiplying the resulting quotient by 413 months.

[12] The value of 66.6 feet is the result of dividing 20 feet by 124 months, and multiplying the resulting quotient by 413 months.

for wise land use to identify those areas of the shorezone that are especially susceptible to erosion.

The projected rate of retreat is less than the long-term recession rates established for three sites within the study area (sites W5, W6, and W7, p. 112). This is because modern retreat values have been less than previous periods, a condition that may be partly due to protective structures along the shore. It is possible, though, that bluff recession in the vicinity of sites K13 through K17 may prove to be greater than projected based on the prediction technique. During the modern period of record this bluff segment was buffered against wave erosion by a relatively wide beach terrace (Figure 25). This terrace, however, has been largely removed and conditions are such that it may not reform. In such a case, future bluff retreat will surely be greater than the modern record would indicate.

Based on the estimated 100-year bluff line position at least 41 existing buildings would be destroyed and the main highway between the cities of Kenosha and Racine would be threatened. These structures may not be saved but future damage can be limited by preventing further construction within the zone of likely bluff top retreat. It is only prudent to establish zoning setback requirements and prohibit situations such as found in Figure 31.

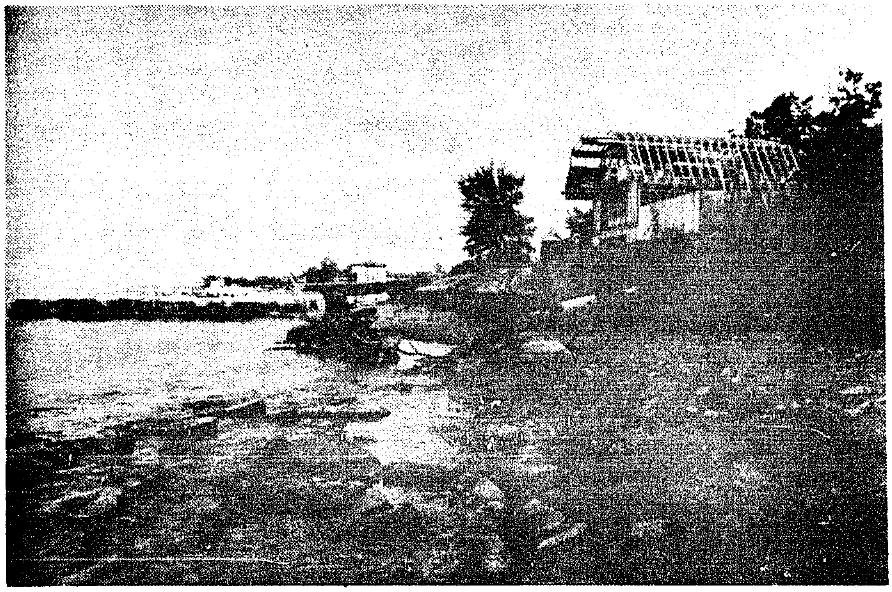

Figure 31. Unwise construction along the Kenosha County, Wisconsin shorezone. Long-term bluff recession in this vicinity has been about five feet per year. This location is at the Centerline / Section 17 / T1N,R23E.

Chapter 5

SUMMARY AND CONCLUSIONS

The conclusions of this study are summarized below as they relate to the three basic objectives of the dissertation.

The first purpose is "To determine long-term bluff crest recession at a number of sites along the Michigan and Wisconsin lakeshores and to compare these findings with selected characteristics of the shorezone." Long-term bluff line changes are determined at 118 locations, 62 in Wisconsin and 56 in Michigan. Individual sites and extended reaches on both sides of Lake Michigan display wide variability in these changes. Long-term recession cannot be related in a meaningful way with sediments or sediment arrangements for bluffs composed of non-eolian material. In contrast, dune bluffs are generally receding at significantly lower long-term rates than bluffs composed of non-dune sediments. Although dune bluffs are probably no less, and may even be more, susceptible to retreat from wave erosion than are bluffs formed in non-dune material, their typically lower long-term values are attributable to dune accretion during low lake level episodes. Consequently, at sand dune locations <u>net</u> long-term recession rates tend to be lower but <u>gross</u> long-term losses may be greater than at non-dune sites.

Variations in rates of long-term recession cannot be directly correlated to factors of ground water activity and bluff height. Ground water seepage, nonetheless, appears to be an important contributor to bluff slope instability; in general, this condition is probably more detrimental to the Wisconsin than to the Michigan lakeshore bluffs. Because perched water tables are common in most high non-dune bluffs they may at least partially account for the lack of correlation between bluff heights and rates of retreat.

Shoreline orientation and fetch appear to influence rates of retreat but beach width cannot be meaningfully related to long-term bluff recession values.

The second objective is "To test the hypothesis that within the segments examined bluff crest recession is greater on the eastern side of the lake." Site data, however, indicate that long-term bluff recession along the opposite shores is statistically similar. Although the Michigan lakeside may expect a higher incidence of incoming deep water storm waves, the strong influence of foredune regeneration and better development of energy dissipating beaches and longshore sand bars on the eastern shorezone probably account for Michigan's rates resembling those of Wisconsin. Findings also disclose that sites in the southern portion of both lakeshores tend to exhibit higher than average retreat rates, and in Wisconsin recession values are significantly lower north, than south, of the city of Port Washington.

The third objective is "To investigate two areas in detail and to predict future bluff crest positions and suggest possible consequences resulting from retreating bluffs at these locations." Modern rates of bluff line change are determined for the Shoreham, Michigan, and northern Kenosha County, Wisconsin, case study areas where most sites experienced retreat. Average annual rates vary with the interval between measurements. Generally the highest rates correspond to periods which contain the greatest percentage of years when lake levels are high. Furthermore, modern rates are found not to be similar to long-term retreat values in the areas studied. This condition is largely attributable to the substantial increase in shore protection structures during the modern era. The temporal and disjunct pattern of these structures greatly influence the point-to-point variation in recession rates and account for the increasing irregularity in bluff appearance. Overall, data imply that bluff protection structures have an adverse effect on shorezone conditions.

A method of predicting future bluff crest positions is also suggested. Using a factor related to the 579 foot lake level, bluff line positions are forecast for the next century in the case study areas. Projected retreat for the Shoreham segment is greater than previous long-term rates established for the area but expected recession for the Kenosha County reach is less than past long-term records indicate. The conflict between past and projected rates of retreat is largely credited to the influence of shore protection structures.

Suggestions for Future Research

During the study it became apparent that certain subjects deserve additional investigation. First, since foredune regeneration appears to retard long-term bluff recession, the relationship between modern foredunes and factors influencing their development and uneven distribution, and their accretion and erosion rates, need to be better understood. Second, it may be helpful to establish the relationship between short-term recession (accretion) rates and the length of a given high (low) lake level period, and the frequency of change between episodes of above and below average water elevations. Third, although a few studies have focused on ascertaining incoming deep water wave energy along the Michigan and Wisconsin shores, there is a need to determine, over wide areas and under varying conditions, the amount of incoming shallow water wave energy which actually reaches the beach and bluff zone and to relate these data to rates of retreat. And last, it would be advantageous to determine more precisely the accumulated effect which increasing numbers of shorezone protection structures have had, and will continue to have, on littoral processes and bluff line evolution.

APPENDICES

APPENDIX A

SHOREZONE TERMINOLOGY USED IN THIS STUDY

Shorezone terminology used in this study is defined in Table A1.

Table A1. Shorezone terminology used in this study.

Backshore	The zone of the shore or beach lying between the foreshore and the shoreland and acted upon by waves only during severe storms, especially when combined with exceptionally high water (Veatch and Humphrys, 1964).
Bank	A landward-facing steep bluff or sharp slope of unconsolidated material landward of the shoreline; the bluff.
Beach	A shore of unconsolidated material, usually sand and/or pebbles (U.S. Army Corps of Engineers, 1973c).
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 or 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.
Bluff Slope	The lakeward-facing inclined surface of the bluff; the bluff face.
Breaker Zone	The area of water bounded by the beach and the plunge line; the plunge line is the line along which the highest waves break (Russell and MacMillan, 1970).
Breakwater	A structure protecting a shore area, harbor, anchorage, or basin from waves; it is usually parallel to the shore and built in the nearshore zone (U.S. Army Corps of Engineers, 1973c).

Table A1 (cont'd.).

Foredune	The front sand dune immediately behind the backshore (U.S. Army Corps of Engineers, 1973c).
Foreshore	The part of the shore, or beach, normally covered by the uprush and backrush of waves (Veatch and Humphrys, 1965).
Groin	A shore protection structure built usually perpendicular to the shoreline in order to trap littoral drift or retard erosion of the shore (U.S. Army Corps of Engineers, 1973c).
Inshore (Zone)	The zone of variable width extending from the shoreline through the breakwater (Gray, McAfee, and Wolf, 1972); essentially the same as the littoral zone.
Jetty	A structure extending into a body of water designed to prevent shoaling of a channel by littoral material and to direct and confine stream flow (U.S. Army Corps of Engineers, 1973c).
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.
Lakeside	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 lakeshore.
Littoral Current	Any current in the littoral zone (inshore zone) caused primarily by wave action, e.g., a longshore or rip current (U.S. Army Corps of Engineers, 1973c).
Littoral Drift	The sedimentary material moved in the littoral zone under the influence of waves and currents (U.S. Army Corps of Engineers, 1973c).

Table A1 (cont'd.).

Littoral Zone	An indefinite zone extending lakeward from the shoreline to just beyond the breaker zone (U.S. Army Corps of Engineers, 1973c); essentially the inshore zone.
Longshore Sand Bar	A low, elongate submerged sand ridge(s), built chiefly by wave action, occurring at some distance from, and extending generally parallel with, the shoreline, and typically separated from the beach by an intervening trough(s) (Gary, McAfee, and Wolf, 1972).
Longshore Current	The littoral current in the breaker zone moving essentially parallel to the shore, usually generated by waves breaking at an angle to the shoreline (U.S. Army Corps of Engineers, 1973c).
Longshore Drift	The material transported by a longshore current (American Geological Institute, 1974).
Nearshore (Zone)	The indefinite zone extending from the shoreline well beyond the breaker zone defining the area of nearshore currents, and including the inshore zone and part of the offshore zone (Gary, McAfee, and Wolf, 1974).
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 (U.S. Army Corps of Engineers, 1973c).
Offshore (Zone)	The shallow bottom lakeward of the breaking waves (Bloom, 1978); this zone is of variable width and is lakeward of the inshore zone (Gary, McAfee, and Wolf, 1972; U.S. Army Corps of Engineers, 1973c).
Revetment	A facing of stone, concrete slabs, etc. built to protect a scarp, embankment, or shore structure against erosion by wave action or currents (U.S. Army Corps of Engineers, 1973c).

Table A1 (cont'd.).

Rip Current	A strong current flowing lakeward from the shore (U.S. Army Corps of Engineers, 1973c).
Riprap	A layer, facing, or protective mound of stones randomly placed to prevent erosion, scour, or sloughing of a structure or embankment; also the stone so used (U.S. Army Corps of Engineers, 1973c).
Seawall	A structure separating land and water areas, primarily designed to prevent erosion and other damage due to wave action (U.S. Army Corps of Engineers, 1973c).
Shore	The zone lakeward of the shoreland over which the ground is alternatively exposed and covered by waves; the shore's upper boundary is the lakeward limit of effective wave action at the base of the bluffs and its lakeward limit is the water line. It may be subdivided into a foreshore and a backshore (Gary, McAfee, and Wolf, 1972).
Shoreland	The zone of land of indefinite width that extends from the base of the bluffs inland to the first major change in terrain feature; the bluff is the lakeward margin of the shoreland (Gary, McAfee, and Wolf, 1972). In essence, it is the lake margin equivalent of "coast," which is an ocean or sea margin term (Veatch and Humphyrs, 1964).
Shoreline	The line separating water and the land; the water line.
Shorezone	The combined nearshore zone, shore, and shoreland.
Water Line	The line separating water and the land; the shoreline.

APPENDIX B

SELECTED CHARACTERISTICS OF THE WISCONSIN AND MICHIGAN STUDY SITES

Selected characteristics of the Wisconsin study sites are described in Table B1 and those of the Michigan sites are displayed in Table B2.

Table B1. Selected characteristics of the Wisconsin study sites.

Key To The Table

Bluff Stratigraphy

ds: Dune sand; eolian deposits of sand size particles.

ws: Water-laid sand; water-deposited sand size particles, with and without pebbles, and to include thin interbedded zones with high percentage of clay or silt-size particles.

cl: Clay; water-deposited sediments of a clay or silty-clay texture.

t: Till; non-stratified, non-sorted glacially deposited sediments which at the study sites are normally of a clay loam texture and which usually include pebbles and/or cobbles.

cov: Covered; the bluff stratigraphy is obscured by overburden.

"Recent Erosion"

"Recent" refers to any time during the present high lake stage (since 1968).

Table B1 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orienta-tion	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
		KENOSHA COUNTY						
W 1	-7.56'	2'-ws	2'	N17½°W	Yes	Yes	No	Yes
W 2	-6.97'	1'-ws	1'	N7½°W	Yes	Yes	No	Yes
W 3	-6.33'	5'-ws	5'	N2½°W	Yes	Yes	No	Yes
W 4	-2.45'	5'-ds / 14'-ws	19'	N4°W	Yes	Yes	No	Yes
W 5[a]	-2.74'	4½'-ws / 28½'-cl	33'	N8°E	Yes	Yes	Yes	Yes
W 6[b]	-2.43'	6½'-ws / 10½'-cl / 6½'-cov / 4'-cl / 4'-t	31½'	N15°E	Yes	Yes	Yes	Yes
		RACINE COUNTY[c]						
W 7[d]	-2.44'	8'-ws / 22'-t	30'	N8°E	Yes	Yes	Yes	Yes
W 8[e]	-0.85'	3'-ws / 28'-t	31'	N12½°E	Yes	Yes	No	Yes
W 9	-0.94'	20'-t	20'	N35½°E	Minor	No	No	No
W10	-1.87'	15'-ws / 9'-t	24'	N48°W	Yes	Yes	No	Yes

Table B1 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orienta-tion	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
W11	-1.24'	31'-t	31'	N45°W	Yes	Yes	No	Yes
W12	-1.77'	2'-cl / 52'-t	54'	N34°W	Yes	Yes	No	Yes
		MILWAUKEE COUNTY						
W13	-3.29'	77'-t / 6'-cl / 7'-t	90'	N17°W	Yes	Yes	Yes	Yes
W14	-1.04'	8'-t / 17½'-ws / 7'-cl / 57½'-cov	90'	N: N6°E S: N7½°E	Yes	Yes	Yes	Yes
W15	-0.65'	15'-t / 23'-ws / 11'-cl / 3'-ws / 6'-cl / 27'-cov	85'	N: N3°E S: N8°W	Yes	Yes	Yes	Yes
W16[f]	-0.81'	70'-lgly cov (prob. complex)	70'	N1°W	No	Minor	No	Yes
		OZAUKEE COUNTY						
W17	-0.13'	30'-t / 28'-ws / 22'-cl	80'	N30½°W	Yes	No	Yes	Yes
W18[g]	-1.97'	15'-t / 80'-cov	95'	N28½°W	Yes	Yes	Yes	Yes
W19	-2.34'	100'-cov (prob. complex)	100'	N14°W	Yes	No	No	Yes

Table B1 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orienta-tion	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
W20	-2.57'	60'-t / 15'-ws / 8'-cov / 3'-cl / 24'-cov (prob. mostly cl)	110'	N7°E	Yes	Yes	Yes	Yes
W21	-2.55'	110'-cov (prob. complex)	110'	N11°E	Yes	Minor	Yes	Yes
W22	-2.90'	110'-cov (prob. complex)	110'	N13°E	Yes	Yes	Yes	Yes
W23	-2.58'	?'-cov / ?'-t / 22'-ws / 21'-cl / 7'-cov	120'	N25°E	Yes	N: Minor S: Yes	Yes	Yes
W24	-2.94'	110'-cov (prob. complex)	110'	N4°E	Yes	Yes	Yes	Yes
W25	-1.44'	poorly exposed: 47'-t / 2'-ws / 12'-t / 5'-ws / 19'-t	85'	N10°E	Yes	Yes	Yes	Yes
W26[h]	-0.41'	25'-t / 20'-cov / 5'-cl / 15½'-ws / 11'-cl / 2'-t / 12'-cov	90'	N: N15°E S: N6½°E	Yes	Yes	Yes	Yes
W27	-0.12'	2'-ws	2'	N14½°E	Yes	Yes	No	Yes
W28	-0.20'	3'-ws	3'	N13½°W	Yes	Yes	No	Yes
		<u>SHEBOYGAN COUNTY</u>						
W29	-0.23'	½'-ds / 2½'-ws	3'	N: N16°W S: N8°E	Yes	Yes	No	Yes

Table B1 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orienta-tion	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
W30	+0.37'	5'-ds	5'	N9°E	Yes	Yes	No	Yes
W31	-0.41'	4-5'-ds	4-5'	N29°E	Yes	Yes	No	Yes
W32	-0.40'	½'-ds / 2½'-ws	3'	N25½°E	Yes	Yes	No	Yes
W33	-0.72'	1'-ds / 4'-ws	4'	N32°E	Yes	Yes	No	Yes
W34	+0.05'	2'-ds / 4'-ws	6'	N28°E	Yes	Yes	No	Yes
W35	+0.06'	3'-ds / 3'-ws	6'	N30°E	Yes	Yes	No	Yes
W36	-1.09'	5'-ds / 4'-ws	9'	N: N3°W S: N12°E	Yes	Yes	No	Yes
W37	-1.07'	10'-ws / 28'-cl	38'	N24°W	Yes	Yes	Yes	Yes
W38	-1.03'	7½'-ws / 5'-cl / 2½'-t / 8'- ws & cl / 10'-cov	33'	N: N7½°W S: N22°W	Yes	Yes	Yes	Yes
W39	-0.92'	22'-t / 4'-ws / 10'-cl / 8'-cov (prob. cl)	44'	N½°W	Yes	Yes	Yes	Yes
W40[i]	-1.10'	4'-ws / 9'-t	13'	N½°E	Yes	Yes	No	Yes
W41	-1.07'	6'-ws / 5'-t / 7'-ws / 28'-cov (prob. lgly t)	46'	N13°W	Yes	Yes	Yes	Yes

Table B1 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orienta-tion	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
W42	-1.59'	10'-t / 3'-ws / 2'-cl / 23½'-cov / 17½'-t	56'	N3½°W	Yes	Yes	Yes	Yes
		MANITOWOC COUNTY						
W43	-1.33'	2½'-t / 2½'-ws / 5'-cl / 35'-cov	45'	N4½°E	Yes	Yes	Yes	Yes
W44	-0.76'	17'-ws / 13'-t / 14'-cov	44'	N12°E	Yes	Yes	Yes	Yes
W45	-0.74'	14'-cov (partly ws) / 10'-t / 16'-ws	40'	N35°E	No	No	No	Yes (old)
W46	-0.40'	3'-cl / 10'-ws / 15'-cl / 17'-cov (prob. lgly t)	45'	N5°E	Yes	Yes	Yes	Yes
W47	-0.27'	17'-ws / 10'-cl / 20'-cov (prob. lgly t)	47'	N15°E	Yes	Yes	Yes	Yes
W48	-0.17'	5½'-ws / 6'-ws w/ abun. pebbles & cobbles / 16'-t	27½'	N23½°E	Yes	Yes	Yes	Yes
W49	-0.73'	6'-ws / 8'-t / 6'-ws w/ abun. pebbles & cobbles / 20'-ws / 15'-cov	55'	N: N18°E S: N37°E	Yes	Yes	Yes	Yes

Table B1 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orienta-tion	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
W50	-1.06'	9'-ws / 7'-cov (prob. ws)	16'	N: N17°W S: N½°W	Yes	Yes	No	Yes
W51	-1.67'	7'-ws / 1'-t	8'	N48½°E	Yes	Yes	No	Yes
W52	-2.63'	3'-cl / 10'-cov	13'	N22°W	Yes	Yes	No	Yes
W53	-1.77'	20'-t	20'	N3°W	Yes	Yes	No	Yes
W54	-0.80'	4'-ws / 5'-t / 9'-ws / 3'-cl / 8'-cov (prob. cl)	29'	N15½°E	Yes	Yes	Yes	Yes
		<u>KEWAUNEE COUNTY</u>						
W55	-0.90'	9'-t / 15'-ws / 10'-cov / 9'-t / 14'-cov	57'	N17°E	Yes	Yes	Yes	Yes
W56	-1.29'	5'-t / 20'-ws / 30'-cov (prob. ws w/ abun. pebbles)	55'	N23°E	Yes	Yes	Yes	Yes
W57	-0.77'	7'-t / 4'-ws / 20'-t / 9'-cov	40'	N11°E	Yes	Yes	Yes	Yes
W58	-0.25'	5'-t / 33'-cov / 10'-ws	48'	N19°E	Yes	Minor	No	Yes
W59	-0.24'	9'-t / 1'-cl / 35'-ws (lgly pebbles & cobbles	45'	N: N5°E S: N19°E	Yes	No	No	Yes

Table B1 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orienta-tion	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
W60	-0.22'	5'-t / 17'-ws / 40'-cov	62'	N15°E	Yes	No	No	Yes
W61	+0.08'	2'-ws	2'	N23°E	Minor	Minor	No	Yes
		<u>DOOR COUNTY</u>						
W62	-0.17'	1'-ds / 3'-ws	4'	N: N25½°E S: N12½°E	Minor	Minor	No	Yes

Table B1 (cont'd.).

Footnotes

[a] Fill material had recently been deposited lakeward of the natural bluff line, artificially extending the bluff crest by 4.5 feet as of August 16, 1976. The resurvey was terminated at a point coinciding with the natural bluff line position.

[b] Fill material had been deposited lakeward of the natural bluff line, artificially extending the bluff crest by 15 feet as of July 3, 1976. Indications are that this filling process will continue. The resurvey was terminated at a point coinciding with the natural bluff line position.

[c] Recession values for most sites in Racine County are inconsistent with those published by Powers (1958) and the U.S. Corps of Engineers (1953); total long-term losses cited in these older references were generally greater than the total bluff line retreat determined in this study. Upon examination of the techniques and data employed by Powers and the Corps it is believed that the values in this present study are the correct ones. Resurveys during this investigation utilized R.L.S. survey maps, dossiers on section and quarter-section locations and publications generated by a recent and ongoing land survey remonumentation program (Southeastern Wisconsin Regional Planning Commission, 1968).

[d] During the present high lake stage but subsequent to "recent" erosion at the bluff crest a seawall had been constructed at the bluff base.

[e] Although there was minor or no "recent" erosion at the bluff base and crest at the section line the bluff has been significantly eroding a short distance to the north.

[f] A municipal groin system extends approximately one-fifth of a mile north and south of the section line and appears to be protecting the bluff very well; the beach zone is relatively wide here. Adjacent and south of the groin system the bluff has been experiencing severe erosion.

[g] Erosion at the bluff crest at the section line was caused by localized slumping a short time prior to the resurvey.

Table B1 (cont'd.).

[h] Bluff erosion and recession appear more severe at this site than the low recession rate indicates. Because the monument at the SW Corner / Section 33 / T11N,R22E could not be located the resurvey to the bluff crest was run from the more distant NW Corner / Section 3 / T10N,R22E. This deviation from the normal procedure may have introduced some error into the calculated retreat value.

[i] The section line coincides with the north facing, southern valley slope of Sevenmile Creek. Several yards south of the section line the lake bluff rises to a height of 37 feet.

Table B2. Selected characteristics of the Michigan study sites.

Key To The Table

Bluff Stratigraphy

ds: Dune sand; eolian deposits of sand size particles.

ws: Water-laid sand; water-deposited sand size particles, with and without pebbles, and to include thin interbedded zones with high percentage of clay or silt size particles.

cl: Clay; water-deposited sediments of a clay or silty-clay texture.

t: Till; non-stratified, non-sorted glacially deposited sediments which at the study sites are normally of a clay loam texture and which usually include pebbles and/or cobbles.

cov: Covered; the bluff stratigraphy is obscured by overburden.

fd: Foredune; the sand dune immediately behind the backshore and fronting the primary bluff. This feature tends to be ephemeral; during higher water periods it generally undergoes erosion while during lower lake elevations it tends to undergo accretion.

prev. fd: Previous foredune; a foredune was present at the beginning of the present high water period in 1968 but had eroded completely by 1976-77.

remn. fd: Remnant of a foredune; only the very last portion of a foredune remains and this may be spaced intermittantly along the lakeshore segment between points where bluff toe erosion has begun.

"Recent Erosion"

"Recent" refers to any time during the present high lake stage (since 1968).

Table B2 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orienta-tion	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
		BERRIEN COUNTY						
M 1	-1.88'	58'-ws	58'	N25°E	Yes	Yes	No	Yes
M 2[a]	-2.16'	7½'-ws / 12½'-t / 5'-ws / 4'-t / 31'-ws / 15'-cov	73'	N24½°E	Yes	Yes	Yes	Yes
M 3	-1.24'	10'-ws / 36'-t / 62'-ws	108'	N38°E	Yes	Yes	Yes	Yes
M 4[b]	-4.30'	12-15'-t / 85-95'-ws	110'	N35°E	Yes	Yes	Yes	Yes
M 5	-2.92'	5'-ws / 54'-t / 51'-ws	110'	N37°E	Yes	No	Yes	Yes
M 6	-2.39'	7'-ws / ±33'-t / ±31'-ws / w/ remn. fd	71'	N35°E	Yes	No	Yes	Yes
		VAN BUREN COUNTY						
M 7	-1.53'	19'-ws / 16'-cl	35'	N: N13°E S: N22°E	Yes	Yes	Yes	Yes
M 8	-2.69'	6'-ws / 35'-t	41'	N: N15°E S: N28°E	Yes	Yes	Yes	Yes

Table B2 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orienta-tion	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
		<u>ALLEGAN COUNTY</u>						
M 9	-1.34'	9'-ws / 12'-cl / 51'-ws	72'	N: N9°E S: N15°E	Yes	Yes	Yes	Yes
M10	-1.54'	20'-ws / 9'-t / 15'-ws / 25'-t	69'	N6°E	Yes	No	Yes	Yes
M11	-0.93'	7'-ws / 48'-t[c]	55'	N5°E	Yes	Yes	Yes	Yes
M12[d]	-0.92'	7'-ds	7'	N11°E	Yes	Yes	No	Yes
M13	-0.94'	7'-ws / 28'-t / 10'-ws	45'	N6°W	Yes	Yes	Yes	Yes
M14	-0.93'	19'-ws / 48'-t / prev. fd	67'	N: N11°E S: N3½°E	Yes	No	Yes	Yes
		<u>OTTAWA COUNTY</u>						
M15	-0.80'	2'-ds / 28'-ws prev. fd	30'	Due N	Yes	Yes	No	Yes
M16	-0.22'	10-15'-ds / 10-15'-ws prev. fd	28'	N1½°W	Yes	Yes	No	Yes
M17	-1.03'	29'-ds	29'	N2°E	Yes	Yes	No	Yes

Table B2 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orienta-tion	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
M18	-0.69'	3'-ds / 40'-ws / prev. fd	43'	N2°E	Yes	Yes	No	Yes
M19[e]	-0.79'	36'-ds / 24'-ws / w/ 2 fd	60'	N9°W	Yes	No	No	Yes
M20	-0.38'	50'-ds / prev. fd	50'	N6°W	Yes	Yes	No	Yes
M21[f]	+0.27'	17'-ds / prev. fd	17'	N6°W	Yes	Yes	No	Yes
M22[g]	-1.00'	5'-ds / 10'-ds or ws? / 8'-ws / 6'-t / prev. fd	29'	N7°W	Yes	Yes	No	Yes
M23[h]	-0.36' +0.06'	42'-ds 23½'-ds	42' 23½'	N13°W	Yes	No Yes	No	No Yes
		MUSKEGON COUNTY						
M24	-2.17'	10'-ds / 40'-cov (prob. ds & ws) / 25'-ws / prev. fd	75'	N26½°W	Yes	Yes	No	Yes

Table B2 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orientation	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
M25	-0.74'	3'-ds / 29'-ws	32'	N24½°W	Yes	Yes	No	Yes
M26[i]	-1.06'	?'-ds / ?'-ws / w/ remn. fd	40'	N26°W	Yes	No	No	No
M27	-1.39'	40'-ws / prev. fd	40'	N24°W	Minor	No[i]	No	No
M28	-1.59'	48'-ds / 58'-ws / prev. fd	106'	N20°W	Yes	No	No	Yes
M29	-1.45'	16'-ws / 2'-t / 65'-ws	83'	N15°W	Yes	Yes	No	Yes
M30	-1.35'	20'-ds / prev. fd	20'	N13½°W	Yes	Yes	No	Yes
		OCEANA COUNTY						
M31[h]	-0.47' 0.00'	36'-ds 18'-ds	36' 18'	N13°W	Yes	No Yes	No	No Yes
M32	+0.31'	25'-ds / prev. fd	25'	N20°W	Yes	Yes	No	Yes
M33	-2.24'	16'-ds / prev. fd	16'	N13°W	Yes	Yes	No	Yes

Table B2 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orientation	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
M34	-0.11'	12'-ds / prev. fd	12'	N2°W	Yes	Yes	No	Yes
M35	-1.99'	15'-ds / prev. fd	15'	N5°W	Yes	Yes	No	Yes
M36[h]	-0.34' +0.77'	37'-ds 15'-ds	37' 15'	N7°E	Yes	No Yes	No	No Yes
		MASON COUNTY						
M37	-0.80'	65'-ws / 100'-t	165'	N14°W	Yes	No	Yes	Yes
M38	-0.65'	114'-ws / 23'-cl / 12'-cov / 12'-ws	170'	N2°W	Yes	Yes	Yes	Yes
M39	+0.70'	16'-ds	16'	N30°W	Yes	Yes	No	Yes
M40	+0.76'	15'-ds	15'	N: N35°E S: N27½°E	Yes	Yes	No	Yes
		MANISTEE COUNTY						
M41	-0.97'	8'-ds / prev. fd	8'	N35°E	Yes	Yes	No	Yes

Table B2 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orienta-tion	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
M42	-0.52'	29'-ds / w/ fd	29'	N16°E	Yes	No	No	Yes
M43	-1.91'	15'-t / 27'-cov (prob. ws) / 26'-ws	68'	N20°E	Yes	Yes	No	Yes
M44	-2.65'	16'-t / 46'-ws	62'	N16½°E	Yes	Yes	No	Yes
M45	-0.99'	2-10'-t / 10-40'-ws / 10-40'-t / w/ remn. fd	78'	N18½°E	No to Slight	No	No	No
M46	-0.80'	10'-ds / prev. fd	10'	N22½°E	Yes	Yes	No	Yes
M47	-1.10'	16'-ds / prev. fd	16'	N27°E	Yes	Yes	No	Yes
M48	-1.74'	6'-ds (poss. ws)	6'	N35°E	Yes	Yes	No	Yes
M49	-0.85'	26'-ds / prev. fd	26'	N17°E	Yes	No	No	Yes

Table B2 (cont'd.).

Site No.	Aver. Ann. Bluff Crest Change GLO Date To 1976-77	Generalized Bluff Stratigraphy	Bluff Height	Shore-line Orienta-tion	"Recent" Erosion At Bluff Base	"Recent" Erosion At Bluff Crest	Visible Ground Water Seepage	Mass-Movement On Slope Below Crest
		BENZIE COUNTY						
M50	-2.62'	10-15'-ds / 6-10'-t / 125-150'-ws/ 10'-t / 2½'-ws / 1½'-t / 3'-cl / 6'-ws / 2'-cl / 15'-t / 35'-ws / 18'-t / 2'-cl / 6'-cov / 16'-ws / 25'-t	310'	N11°W	Yes	No	Yes	Yes
		LEELANAU COUNTY						
M51	-0.06'	13'-ds / prev. fd	13'	N4°E	Yes	Yes	No	Yes
M52	-0.34'	15'-ds / w/ remn. fd	15'	N4°W	Yes	No	No	Yes
M53[h]	-0.27' +0.29'	14'-ds 7'-ds	14' 7'	N17°E	Yes Yes	No Yes	No	No Yes
M54	-0.39'	30'-t / w/ remn. fd & ds veneering slope	30'	N: N11½°E S: N22°E	Yes (on fd)	No	No	No
M55	-1.52'	41'-t / 63'-ws	104'	N5°E	Yes	No	No	Yes
M56	-0.03'	8'-ds / prev. fd	8'	W: N37°W E: N87°W	Minor	Minor	No	Yes

Table B2 (cont'd.).

Footnotes

[a] The bluff was receding rapidly until 1971 at which time a multi-million dollar steel pile and limestone block revetment and groin system was constructed northward from a point just south of this section line in order to protect highway and railroad rights-of-way. Bluff recession has been minimal since 1971.

[b] The section line intersects the bluff crest at an acute angle and at a point where a very large slump and some gullying have occurred. Although bluff erosion and recession have been significant along this reach of the shorezone the long-term recession rate for this site is probably somewhat higher than is representative of the reach as a whole.

[c] This till includes large pockets and zones of sand and/or gravel in the lower 20 feet.

[d] The section line coincides with the northern slope of a ravine through which intermittant grainage flows. Except for a small cut the ravine mouth is blocked by low dunes; the resurvey measurement terminated at the lakeward crest of these dunes. To the north and south bluffs rise 43 to 50 feet and are composed of sand overlying till.

[e] Because of the rounded nature of the crest and pedestrian traffic, the position of the bluff line is somewhat ambiguous.

[f] Although results of this resurvey indicated long-term net accertion comparison with a R.L.S. property survey indicated a bluff crest loss of 8.8 feet between 1974 and 1976.

[g] The resurvey measurement was carried to a line connecting the bluff crest on either side of the section line easement. The bluff at the easement was notched in 1973 when a drainage pipe was installed.

[h] At four dune sites (M23, M31, M36, and M53) two distinct bluff crests are recognized. The lakeward crest is a bluff line of a lower-relief dune terrace which fronts the more landward crest of a somewhat higher-relief dune feature. Because of the situation and the lack of clarity in the GLO notes it was not possible positively to ascertain to which point the GLO measurement terminated; consequently, this study's measurements were carried to each of the two possible crest lines and corresponding recession

Table B2 (cont'd.).

rates then determined. In the table the upper figure pertains to measurements to the crest line of the somewhat higher-relief landward dune form and the lower figure to measurements to the bluff line of the lower-relief lakeward dune feature. In three of the four cases measurements to either crest indicated relatively small changes in bluff line position relative to the GLO surveys. The recession or accretion rates determined for the four sites are not included in any of the quantitative analysis performed in this study. In no way does this exclusion affect any of the conclusions reached and, in fact, their inclusion would only increase support for the findings reported.

[i] During the high lake period of the early 1950's the water level was up against the base of the present bluff. However, during the low lake stage in the late 1950's and early 1960's a foredune terrace three to nine feet in height and at least 65 to 75 feet in width had formed in front of the present bluff; this foredune has largely been removed by wave erosion during the present high water period.

[i] Although there has been only minor "recent" erosion at the bluff crest at the section line location erosion has reached the crest several hundred feet to the north and south.

APPENDIX C

LONG-TERM BLUFF LINE CHANGES AND LOCATIONS OF THE WISCONSIN AND MICHIGAN STUDY SITES

Long-term bluff line changes and locations of the Wisconsin study sites are described in Table C1 and those of the Michigan sites are displayed in Table C2.

Table C1. Long-term bluff line changes and locations of the Wisconsin study sites.

Site No.	Section Line Location	Year of GLO Survey	Resur-vey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
	KENOSHA COUNTY							
W 1	South Line/Sec 29/T1N,R23E	1835	1976	SW Cor	2591.82' (789.99 m)	1525.50' (464.97 m)	-1066.32' (-325.01 m)	-7.56' (-2.304 m)
W 2	South Line/Sec 20/T1N,R23E	1835	1976	SW Cor	1639.44' (499.70 m)	657.00' (200.25 m)	- 982.44' (-299.45 m)	-6.97' (-2.124 m)
W 3	South Line/Sec 17/T1N,R23E	1835	1976	SW Cor	1268.52' (386.64 m)	376.00' (114.60 m)	- 892.52' (-272.04 m)	-6.33' (-1.929 m)
W 4	South Line/Sec 8/T1N,R23E	1835	1976	SW Cor	975.48' (297.33 m)	630.00' (192.02 m)	- 345.58' (-105.33 m)	-2.45' (-0.747 m)
W 5[a]	South Line/Sec 7/T2N,R23E	1836	1976	S¼ Cor	2950.86' (899.42 m)	2566.94' (782.40 m)	- 383.92' (-117.02 m)	-2.74' (-0.835 m)
W 6[b]	South Line/Sec 5/T2N,R23E	1836	1976	SW Cor	1581.36' (482.00 m)	1241.67' (378.46 m)	- 339.69' (-103.54 m)	-2.43' (-0.741 m)
	RACINE COUNTY[c]							
W 7[d]	South Line/Sec 32/T3N,R23E	1835	1976	S¼ Cor	435.60' (132.77 m)	91.80' (27.98 m)	- 343.80' (-104.79 m)	-2.44' (-0.744 m)

Table C1 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resur-vey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
W 8	North Line/Sec 4/T3N,R23E	1835	1976	N¼ Cor	1849.98' (563.87 m)	1729.48' (527.15 m)	- 120.50' (- 36.73 m)	-0.85' (-0.259 m)
W 9	South Line/Sec 27/T4N,R23E	1836	1976	SW Cor	1058.64' (322.67 m)	926.50' (282.40 m)	- 132.14' (- 40.28 m)	-0.94' (-0.287 m)
W10	South Line/Sec 16/T4N,R23E	1836	1976	S¼ Cor	1028.28' (313.42 m)	766.12' (233.51 m)	- 262.16' (- 81.13 m)	-1.87' (-0.570 m)
W11	South Line/Sec 8/T4N,R23E	1836	1976	S¼ Cor	1081.08' (329.51 m)	907.20' (276.51 m)	- 173.88' (- 53.00 m)	-1.24' (-0.378 m)
W12	South Line/Sec 6/T4N,R23E	1836	1976	S¼ Cor	2288.88' (697.65 m)	2041.17' (622.15 m)	- 247.71' (- 75.50 m)	-1.77' (-0.539 m)
	<u>MILWAUKEE COUNTY</u>							
W13	South Line/Sec 25/T5N,R22E	1836	1976	S¼ Cor	2747.25' (837.36 m)	2286.54' (696.94 m)	- 460.71' (-140.42 m)	-3.29' (-1.003 m)
W14	South Line/Sec 36/T6N,R22E	1836	1976	SW Cor	1049.40' (319.86 m)	904.30' (275.63 m)	- 145.10' (- 44.23 m)	-1.04' (-0.317 m)
W15	South Line/Sec 25/T6N,R22E	1836	1976	SW Cor	1822.92' (555.63 m)	1732.30' (528.01 m)	- 90.62' (- 27.62 m)	-0.65' (-0.198 m)

Table C1 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resurvey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
W16[e]	South Line/Sec 24/T6N,R22E	1836	1976	SW Cor	1273.14' (388.05 m)	1160.40' (353.69 m)	- 112.74' (- 34.36 m)	-0.81' (-0.247 m)
	OZAUKEE COUNTY							
W17	South Line/Sec 33/T9N,R22E	1833	1976	S¼ Cor	462.00' (140.82 m)	443.66' (135.23 m)	- 18.34' (- 5.59 m)	-0.13' (-0.040 m)
W18	South Line/Sec 21/T9N,R22E	1835	1977	SW Cor	686.40' (209.21 m)	406.00' (123.75 m)	- 280.40' (- 85.47 m)	-1.97' (-0.600 m)
W19	South Line/Sec 17/T9N,R22E	1835	1977	S¼ Cor	1132.56' (345.20 m)	800.80' (244.08 m)	- 331.76' (-101.12 m)	-2.34' (-0.713 m)
W20	South Line/Sec 8/T9N,R22E	1835	1976	S¼ Cor	775.50' (236.37 m)	413.00' (125.88 m)	- 362.50' (-110.49 m)	-2.57' (-0.783 m)
W21	South Line/Sec 5/T9N,R22E	1835	1976	S¼ Cor	1912.68' (582.98 m)	1552.43' (473.18 m)	- 360.25' (-109.80 m)	-2.55' (-0.777 m)
W22	South Line/Sec 33/T10N,R22E	1833	1976	SW Cor	550.44' (167.77 m)	135.50' (41.30 m)	- 414.94' (-126.47 m)	-2.90' (-0.884 m)
W23	South Line/Sec 28/T10N,R22E	1835	1977	SW Cor	2524.50' (769.47 m)	2157.55' (657.62 m)	- 366.95' (-111.85 m)	-2.58' (-0.786 m)

Table C1 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resur-vey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
W24	South Line/Sec 16/T10N,R22E	1835	1977	S¼ Cor	2640.00' (804.67 m)	2222.41' (677.39 m)	- 417.59' (-127.28 m)	-2.94' (-0.896 m)
W25	South Line/Sec 10/T10N,R22E	1835	1976	SW Cor	429.00' (130.76 m)	225.50' (68.73 m)	- 203.50' (- 62.03 m)	-1.44' (-0.439 m)
W26[f]	North Line/Sec 3/T10N,R22E	1833	1977	NW Cor	2315.28' (705.70 m)	2256.40' (687.75 m)	- 58.88' (- 17.95 m)	-0.41' (-0.125 m)
W27	South Line/Sec 25/T12N,R22E	1835	1976	S¼ Cor	2188.56' (667.07 m)	2171.23' (661.79 m)	- 17.33' (- 5.28 m)	-0.12' (-0.037 m)
W28	South Line/Sec 18/T12N,R23E	1835	1976	SW Cor	1942.38' (592.04 m)	1913.78' (583.32 m)	- 28.60' (- 8.72 m)	-0.20' (-0.061 m)
	SHEBOYGAN COUNTY							
W29	South Line/Sec 31/T13N,R23E	1834	1976	SW Cor	2409.00' (734.26 m)	2376.35' (724.31 m)	- 32.65' (- 9.95 m)	-0.23' (-0.070 m)
W30	South Line/Sec 30/T13N,R23E	1835	1976	SW Cor	2230.14' (679.75 m)	2282.41' (695.68 m)	+ 52.27' (+ 15.93 m)	+0.37' (+0.113 m)
W31	South Line/Sec 17/T13N,R23E	1835	1976	SW Cor	1261.92' (384.63 m)	1203.69' (366.88 m)	- 58.23' (- 17.75 m)	-0.41' (-0.125 m)

Table C1 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resurvey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
W32	South Line/Sec 8/T13N,R23E	1835	1976	SW Cor	1397.22' (425.87 m)	1340.89' (408.70 m)	- 56.33' (- 17.17 m)	-0.40' (-0.122 m)
W33	South Line/Sec 4/T13N,R23E	1835	1976	SW Cor	1712.70' (522.03 m)	1610.85' (490.99 m)	- 101.85' (- 31.04 m)	-0.72' (-0.219 m)
W34	South Line/Sec 27/T14N,R23E	1835	1976	SW Cor	2022.90' (616.58 m)	2029.21' (618.50 m)	+ 6.45' (+ 1.97 m)	+0.05' (+0.015 m)
W35	South Line/Sec 14/T14N,R23E	1835	1976	SW Cor	2279.64' (694.83 m)	2287.76' (697.31 m)	+ 8.12' (+ 2.47 m)	+0.06' (+0.018 m)
W36	South Line/Sec 2/T14N,R23E	1835	1976	S¼ Cor	2072.40' (631.67 m)	1918.93' (584.89 m)	- 153.47' (- 46.78 m)	-1.09' (-0.332 m)
W37	North Line/Sec 3/T15N,R23E	1834	1977	N¼ Cor	1687.62' (514.39 m)	1535.00' (467.87 m)	- 152.65' (- 46.53 m)	-1.07' (-0.326 m)
W38	South Line/Sec 27/T16N,R23E	1835	1976	SW Cor	3379.20' (1029.98 m)	3233.50' (985.57 m)	- 145.70' (- 44.41 m)	-1.03' (-0.314 m)
W39	South Line/Sec 22/T16N,R23E	1835	1976	SW Cor	2942.28' (896.81 m)	2813.20' (857.46 m)	- 129.08' (- 39.34 m)	-0.92' (-0.280 m)
W40	South Line/Sec 15/T16N,R23E	1835	1976	SW Cor	3411.54' (1039.84 m)	3255.74' (992.35 m)	- 155.80' (- 47.49 m)	-1.10' (-0.335 m)

Table C1 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resurvey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
W41	South Line/Sec 10/T16N,R23E	1835	1976	SW Cor	2130.48' (649.37 m)	1979.50' (603.35 m)	- 150.98' (- 46.02 m)	-1.07' (-0.326 m)
W42	South Line/Sec 3/T16N,R23E	1835	1977	SW Cor	1469.16' (447.80 m)	1243.50' (379.12 m)	- 225.66' (- 68.78 m)	-1.59' (-0.485 m)
	<u>MANITOWOC COUNTY</u>							
W43	South Line/Sec 27/T17N,R23E	1834	1976	S¼ Cor	1370.82' (417.83 m)	1181.90' (360.24 m)	- 188.92' (- 57.58 m)	-1.33' (-0.405 m)
W44[g]	South Line/Sec 14/T17N,R23E	1834	1976	SW Cor	646.14' (196.94 m)	538.27' (164.06 m)	- 107.87' (- 32.88 m)	-0.76' (-0.232 m)
W45[g]	South Line/Sec 11/T17N,R23E	1834	1976	S¼ Cor	660.00' (201.17 m)	555.22' (169.23 m)	- 104.78' (- 31.94 m)	-0.74' (-0.226 m)
W46	South Line/Sec 36/T18N,R23E	1834	1977	SW Cor	891.00' (271.58 m)	834.20' (254.26 m)	- 56.80' (- 17.31 m)	-0.40' (-0.121 m)
W47	South Line/Sec 24/T18N,R23E	1834	1976	W1/16 Cor	2170.74' (661.64 m)	2132.68' (650.04 m)	- 38.06' (- 11.60 m)	-0.27' (-0.082 m)
W48	South Line/Sec 13/T18N,R23E	1834	1976	E1/16 Cor	1234.20' (376.18 m)	1209.67' (368.71 m)	- 24.53' (- 7.48 m)	-0.17' (-0.052 m)

Table C1 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resurvey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
W49	South Line/Sec 5/T18N,R24E	1834	1976	SW Cor	1168.20' (356.07 m)	1064.50' (324.46 m)	- 103.70' (- 31.61 m)	-0.73' (-0.223 m)
W50	South Line/Sec 32/T19N,R24E	1834	1976	SW Cor	1907.40' (581.38 m)	1756.58' (535.41 m)	- 150.82' (- 45.97 m)	-1.06' (-0.323 m)
W51	West Line/Sec 10/T19N,R24E	1835	1976	SW Cor	891.00' (271.58 m)	655.30' (199.74 m)	- 235.70' (- 71.84 m)	-1.67' (-0.509 m)
W52[h]	South Line/Sec 13/T21n,R24E	1834	1976	SW Cor	1905.42' (580.77 m)	1532.18' (467.01 m)	- 373.24' (-113.76 m)	-2.63' (-0.802 m)
W53	South Line/Sec 2/T21N,R24E	1834	1976	S¼ Cor	2188.56' (667.07 m)	1937.55' (590.57 m)	- 251.01' (- 76.51 m)	-1.77' (-0.539 m)
W54	North Line/Sec 2/T21N,R24E	1834	1976	N¼ Cor	2502.06' (762.63 m)	2387.96' (727.85 m)	- 114.10' (- 34.78 m)	-0.80' (-0.244 m)
	KEWAUNEE COUNTY							
W55	South Line/Sec 18/T22N,R25E	1835	1976	SW Cor	660.00' (201.17 m)	533.44' (162.59 m)	- 126.56' (- 38.58 m)	-0.90' (-0.274 m)
W56[g]	South Line/Sec 8/T23N,R25E	1834	1976	SW Cor	2377.32' (724.61 m)	2194.26' (668.81 m)	- 183.06' (- 55.80 m)	-1.29' (-0.393 m)

Table C1 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resurvey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
W57[h]	South Line/Sec 5/T23N,R25E	1834	1976	S¼ Cor	827.64' (252.26 m)	718.38' (218.96 m)	- 109.26' (- 33.30 m)	-0.77' (-0.235 m)
W58	South Line/Sec 29/T24N,R25E	1834	1976	SW Cor	4884.00' (1488.64 m)	4884.00' (1477.91 m)	- 35.21' (- 10.73 m)	-0.25' (-0.076 m)
W59[h]	South Line/Sec 21/T24N,R25E	1834	1976	SW Cor	1653.30' (503.93 m)	1618.96' (493.46 m)	- 34.34' (- 10.47 m)	-0.24' (-0.073 m)
W60[h]	South Line/Sec 16/T24N,R25E	1834	1976	SW Cor	2373.36' (723.40 m)	2342.00' (713.84 m)	- 31.36' (- 9.56 m)	-0.22' (-0.067 m)
W61	North Line/Sec 3/T24N,R25E	1834	1976	W1/16 Cor	2319.90' (707.11 m)	2331.34' (710.59 m)	+ 11.40' (+ 3.47 m)	+0.08' (+0.024 m)
	DOOR COUNTY							
W62	South Line/Sec 4/T26N,R26E	1835	1976	S¼ Cor	2593.80' (790.59 m)	2570.30' (783.43 m)	- 23.50' (- 7.16 m)	-0.17' (-0.052 m)

Table C1 (cont'd.).

Footnotes

[a] Fill material had recently been deposited lakeward of the natural bluff line, artificially extending the bluff crest by 4.5 feet as of August 16, 1976. The resurvey was terminated at a point coinciding with the natural bluff line position.

[b] Fill material had been deposited lakeward of the natural bluff line, artificially extending the bluff crest by 15 feet as of July 3, 1976. Indications are that this filling process will continue. The resurvey was terminated at a point coinciding with the natural bluff line position.

[c] Recession values for most sites in Racine County are inconsistent with those published by Powers (1958) and the U.S. Army Corps of Engineers (1953); total long-term losses cited in these older references were generally greater than the total bluff line retreat determined in this study. Upon examination of the techniques and data employed by Powers and the Corps it is believed that the values in this present study are the correct ones. Resurveys during this investigation utilized R.L.S. survey maps, dossiers on section and quarter-section locations and publications generated by a recent and ongoing land survey remonumentation program (Southeastern Wisconsin Regional Planning Commission, 1968).

[d] During the present high lake stage but subsequent to "recent" erosion at the bluff crest a seawall had been constructed at the bluff base.

[e] A municipal groin system extends approximately one-fifth of a mile north and south of the section line and appears to be protecting the bluff very well; the beach zone is relatively wide here. Adjacent and south of the groin system the bluff is experiencing severe erosion.

[f] Bluff erosion and recession appear more severe at this site than the low recession rate indicates. Because the monument at the SW Corner / Section 33 / T11N,R22E could not be located the resurvey to the bluff crest was run from the more distant NW Corner / Section 3 / T10N,R22E. This deviation from the normal procedure may have introduced some error into the calculated retreat value.

[g] The section line from the monumented section corner to the bluff crest was determined by a due east magnetic compass bearing.

Table C1 (cont'd.).

[h] Although the section or quarter-section corner was not visually monumented the resurvey most likely originated from a point within plus or minus three feet of the actual corner. The section line from the assumed corner to tbe bluff was determined by a due east magnetic compass bearing.

Table C2. Long-term bluff line changes and locations of the Michigan study sites.

Site No.	Section Line Location	Year of GLO Survey	Resur-vey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
	BERRIEN COUNTY							
M 1	South Line/Sec 4/T5S,R19W	1829	1977	SE Cor	957.00' (291.69 m)	678.87' (206.92 m)	- 278.13' (- 84.77 m)	-1.88' (-0.573 m)
M 2[a]	North Line/Sec 3/T5S,R19W	1829	1977	N¼ Cor	1225.62' (373.57 m)	906.10' (276.18 m)	- 319.52' (- 97.39 m)	-2.16' (-0.658 m)
M 3	South Line/Sec 6/T4S,R18W	1830	1977	S¼ Cor	2013.00' (613.56 m)	1830.65' (557.98 m)	- 182.35' (- 55.58 m)	-1.24' (-0.378 m)
M 4[b]	North Line/Sec 6/T4S,R18W	1830	1977	NE Cor	1788.60' (545.17 m)	1156.78' (352.59 m)	- 631.82' (-192.58 m)	-4.30' (-1.311 m)
M 5	South Line/Sec 29/T3S,R18W	1830	1977	SE Cor	2937.00' (895.20 m)	2507.10' (764.16 m)	- 429.90' (-131.03 m)	-2.92' (-0.890 m)
M 6	South Line/Sec 21/T3S,R18W	1830	1977	S¼ Cor	1650.00' (502.92 m)	1303.71' (397.37 m)	- 346.29' (-105.55 m)	-2.39' (-0.728 m)
	VAN BUREN COUNTY							
M 7	South Line/Sec 21/T1N,R17W	1830	1977	S¼ Cor	1188.00' (362.10 m)	962.79' (293.46 m)	- 225.21' (- 68.64 m)	-1.53' (-0.466 m)

Table C2 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resurvey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
M 8	South Line/Sec 9/T1S,R17W	1830	1977	SE Cor	995.94' (303.56 m)	600.90' (183.15 m)	- 395.04' (-120.41 m)	-2.69' (-0.820 m)
	<u>ALLEGAN COUNTY</u>							
M 9	South Line/Sec 12/T1N,R17W	1831	1977	SE Cor	1059.96' (323.08 m)	864.00' (263.35 m)	- 195.96' (- 59.73 m)	-1.34' (-0.408 m)
M10	North Line/Sec 6/T1N,R16W	1831	1977	NE Cor	5040.42' (1536.32 m)	4816.17' (1467.97 m)	- 224.25' (- 68.35 m)	-1.54' (-0.469 m)
M11	South Line/Sec 19/T2N,R16W	1831	1977	S¼ Cor	1051.38' (320.46 m)	915.30' (278.98 m)	- 136.08' (- 41.48 m)	-0.93' (-0.283 m)
M12[c]	South Line/Sec 18/T2N,R16W	1831	1977	SE Cor	2742.30' (835.85 m)	2608.58' (795.10 m)	- 133.72' (- 40.76 m)	-0.92' (-0.280 m)
M13	South Line/Sec 29/T2N,R16W	1831	1977	S¼ Cor	1618.32' (493.26 m)	1481.45' (451.55 m)	- 136.87' (- 41.72 m)	-0.94' (-0.287 m)
M14	South Line/Sec 17/T3N,R16W	1831	1977	S¼ Cor	2006.40' (611.55 m)	1871.28' (570.37 m)	- 135.12' (- 41.18 m)	-0.93' (-0.283 m)

Table C2 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resurvey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
	<u>OTTAWA COUNTY</u>							
M15	South Line/Sec 16/T5N,R16W	1832	1977	S¼ Cor	924.00' (281.64 m)	808.00' (246.28 m)	- 116.00' (- 35.36 m)	-0.80' (-0.243 m)
M16	South Line/Sec 9/T5N,R16W	1832	1977	S¼ Cor	891.00' (271.58 m)	858.40' (261.64 m)	- 32.60' (- 9.94 m)	-0.22' (-0.067 m)
M17	South Line/Sec 4/T5N,R16W	1832	1977	S¼ Cor	778.80' (237.38 m)	629.50' (191.87 m)	- 149.30' (- 45.51 m)	-1.03' (-0.314 m)
M18	South Line/Sec 33/T6N,R16W	1832	1977	S¼ Cor	754.38' (229.94 m)	653.90' (199.31 m)	- 100.48' (- 30.63 m)	-0.69' (-0.210 m)
M19[d]	South Line/Sec 28/T6N,R16W	1832	1977	S¼ Cor	831.60' (253.47 m)	717.68' (218.75 m)	- 113.92' (- 34.72 m)	-0.79' (-0.241 m)
M20	South Line/Sec 33/T7N,R16W	1832	1977	S¼ Cor	1716.00' (523.04 m)	1660.22' (506.04 m)	- 55.78' (- 17.00 m)	-0.38' (-0.116 m)
M21[e]	South Line/Sec 28/T7N,R16W	1832	1976	S¼ Cor	2046.00' (623.62 m)	2084.41' (635.33 m)	+ 38.41' (+ 11.71 m)	+0.27' (+0.082 m)
M22[f]	South Line/Sec 17/T7N,R16W	1832	1977	SE Cor	429.00' (130.76 m)	283.30' (86.35 m)	- 145.70 (- 44.41 m)	-1.00' (-0.305 m)

Table C2 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resur-vey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
M23[g]	South Line/Sec 32/T8N,R16W	1832	1977	S¼ Cor	462.00' (140. 82 m)	470.00' 410.20' 143.26 m 125.03 m	+ 8.00' - 51.80' + 2.44 m - 15.79 m	+0.06' -0.36' +0.018 m -0.110 m
	MUSKEGON COUNTY							
M24	South Line/Sec 8/T10N,R17W	1837	1977	S¼ Cor	2593.80' (790.59 m)	2289.57' (697.86 m)	- 304.23' (- 92.73 m)	-2.17' (-0.661 m)
M25	South Line/Sec 6/T10N,R17W	1837	1977	SE Cor	2393.82' (729.64 m)	2289.60' (697.87 m)	- 104.22' (- 31.77 m)	-0.74' (-0.226 m)
M26[h]	North Line/Sec 1/T10N,R18W	1836	1977	NE Cor	943.80' (287.67 m)	794.00' (242.01 m)	- 149.80' (- 45.66 m)	-1.06' (-0.323 m)
M27	South Line/Sec 30/T11N,R17W	1837	1977	S¼ Cor	1848.00' (563.27 m)	1653.59' (504.01 m)	- 194.41' (- 59.26 m)	-1.39' (-0.424 m)
M28[i]	South Line/Sec 35/T12N,R18W	1837	1977	S¼ Cor	1089.00' (331.93 m)	865.75' (263.88 m)	- 223.25' (- 68.05 m)	-1.59' (-0.485 m)

Table C2 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resurvey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
M29	South Line/Sec 27/T12N,R18W	1837	1977	SE Cor	224.40' (68.40 m)	21.50' (6.55 m)	- 202.90' (- 61.84 m)	-1.45' (-0.442 m)
M30	South Line/Sec 15/T12N,R18W	1837	1977	S¼ Cor	458.70' (139.81 m)	269.50' (82.14 m)	- 189.20' (- 57.67 m)	-1.35' (-0.411 m)
	OCEANA COUNTY							
M31[9]	South Line/Sec 33/T13N,R18W	1837	1977	SE Cor	1155.00' (352.04 m)	$\frac{1155.00'}{1089.00'}$ $\frac{352.04\text{ m}}{331.93\text{ m}}$	$\frac{0.00'}{-66.00'}$ $\frac{0.00\text{ m}}{-20.17\text{ m}}$	$\frac{0.00'}{-0.47'}$ $\frac{0.000\text{ m}}{-0.143\text{ m}}$
M32	South Line/Sec 24/T14N,R18W	1837	1977	SE Cor	2057.88' (627.24 m)	2100.76' (640.31 m)	+ 42.88' (+ 13.07 m)	+0.31' (+0.094 m)
M33	South Line/Sec 13/T14N,R19W	1837	1977	SE Cor	4125.00' (1257.30 m)	3810.80' (1161.53 m)	- 314.20' (- 95.77 m)	-2.24' (-0.683 m)
M34	South Line/Sec 2/T14N,R19W	1837	1977	SE Cor	627.00' (191.11 m)	612.25' (186.61 m)	- 14.75' (- 4.50 m)	-0.11' (-0.034 m)
M35	South Line/Sec 35/T15N,R19W	1838	1977	SE Cor	726.00' (221.28 m)	448.80' (136.79 m)	- 277.20' (- 84.49 m)	-1.99' (-0.607 m)

Table C2 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resurvey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
M36[9]	South Line/Sec 2/T16N,R18W	1838	1977	S¼ Cor	810.00' (247.03 m)	916.90' 762.63' 279.47 m 232.45 m	+ 106.42' - 47.85' + 32.44 m - 14.58 m	+0.77' -0.34' +0.235 m -0.104 m
	MASON COUNTY							
M37	South Line/Sec 10/T17N,R18W	1838	1977	SE Cor	541.20' (164.96 m)	429.80' (131.00 m)	- 111.40' (- 33.95 m)	-0.80' (-0.244 m)
M38	South Line/Sec 34/T18N,R18W	1838	1977	SE Cor	1801.80' (549.19 m)	1715.10' (522.76 m)	- 86.70' (- 26.43 m)	-0.62' (-0.189 m)
M39	South Line/Sec 19/T19N,R18W	1838	1977	SE Cor	350.46' (106.82 m)	448.10' (136.58 m)	+ 97.64' (+ 29.76 m)	+0.70' (+0.213 m)
M40	South Line/Sec 14/T20N,R18W	1839	1977	SE Cor	1108.80' (337.96 m)	1213.05' (369.74 m)	+ 104.25' (+ 31.78 m)	+0.76' (+0.232 m)
	MANISTEE COUNTY							
M41	South Line/Sec 28/T21N,R17W	1839	1977	S¼ Cor	245.52' (74.83 m)	111.00' (33.83 m)	- 134.52' (- 41.00 m)	-0.97' (-0.296 m)

Table C2 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resur-vey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
M42	South Line/Sec 15/T21N,R17W	1839	1977	SE Cor	2729.76' (832.03 m)	2657.52' (810.01 m)	- 72.24' (- 22.02 m)	-0.52' (-0.158 m)
M43	Centerline/Sec 15/T21N,R17W (S. Indian Reserve Line)	1847	1977	E¼ Cor	1923.24' (586.20 m)	1674.33' (510.34 m)	- 248.91' (- 75.87 m)	-1.91' (-0.582 m)
M44	South Line/Sec 10/T21N,R17W	1847	1977	SE Cor	1345.08' (409.98 m)	1000.50' (304.95 m)	- 344.58' (-105.03 m)	-2.65' (-0.808 m)
M45	South Line/Sec 25/T22N,R17W	1847	1977	S¼ Cor	1650.00' (502.92 m)	1521.00' (463.60 m)	- 129.00' (- 39.32 m)	-0.99' (-0.302 m)
M46	South Line/Sec 24/T22N,R17W	1847	1977	SE Cor	2215.62' (675.32 m)	2151.21' (655.69 m)	- 64.41' (- 19.63 m)	-0.50' (-0.152 m)
M47	Centerline/Sec 24/T22N,R17W (N. Indian Reserve Line)	1847	1977	E¼ Cor	1048.08' (319.45 m)	905.10' (275.87 m)	- 142.98' (- 43.58 m)	-1.10' (-0.335 m)
M48	South Line/Sec 5/T22N,R16W	1839	1977	S¼ Cor	1658.58' (505.54 m)	1418.90' (432.48 m)	- 239.68' (- 73.05 m)	-1.74' (-0.530 m)
M49	South Line/Sec 16/T23N,R16W	1839	1977	S¼ Cor	986.70' (300.75 m)	869.67' (265.08 m)	- 117.03' (- 35.67 m)	-0.85' (-0.259 m)

Table C2 (cont'd.).

Site No.	Section Line Location	Year of GLO Survey	Resurvey: This Study	Point of Survey Origin	GLO Distance To "Meander Line"	1976-77 Distance To Bluff Crest	Bluff Crest Change GLO Date To 1976-77	Aver. Ann. Bluff Crest Change GLO Date To 1976-77
	<u>BENZIE COUNTY</u>							
M50	South Line/Sec 3/T25N,R16W	1838	1977	SE Cor	924.00' (281.64 m)	560.32' (170.79 m)	- 363.68' (-110.85 m)	-2.62' (-0.799 m)
	<u>LEELANAU COUNTY</u>							
M51	South Line/Sec 13/T28N,R15W	1850	1977	SE Cor	1865.16' (568.50 m)	1857.82' (566.26 m)	- 7.34' (- 2.24 m)	-0.06' (-0.018 m)
M52	South Line/Sec 12/T28N,R15W	1850	1977	SE Cor	1955.58' (596.06 m)	1911.83' (582.73 m)	- 43.75' (- 13.34 m)	-0.34' (-0.104 m)
M53[g]	South Line/Sec 11/T29N,R14W	1850	1977	S¼ Cor	313.50' (95.55 m)	349.89' 278.89' 106.65 m 85.01 m	+ 36.39' - 34.61' + 11.09 m - 10.55 m	+0.29' -0.27' +0.088 m -0.082 m
M54	South Line/Sec 36/T30N,R14W	1850	1977	SE Cor	1353.00' (412.39 m)	1302.90' (397.12 m)	- 50.10' (- 15.27 m)	-0.39' (-0.119 m)
M55	South Line/Sec 17/T30N,R12W	1851	1977	SE Cor	258.06 (78.66 m)	66.00' (20.17 m)	- 192.06' (- 58.54 m)	-1.52' (-0.463 m)
M56	East Line/Sec 15/T32N,R11W	1855	1977	SE Cor	1452.00' (442.57 m)	1448.36' (441.46 m)	- 3.64' (- 1.11 m)	-0.03' (-0.009 m)

Table C2 (cont'd.).

Footnotes

[a] The bluff was receding rapidly until 1971 at which time a multi-million dollar steel pile and limestone block revetment and groin system was constructed northward from a point just south of this section line in order to protect highway and railroad right-of-ways. Bluff recession has been minimal since 1971.

[b] The section line intersects the bluff crest at an acute angle and at a point where a very large slump and some gullying have occurred. Although bluff erosion and recession have been significant along this reach of the shorezone the long-term recession rate for this site is probably somewhat higher than is representative of the reach as a whole.

[c] The section line coincides with the northern slope of a ravine through which intermittant drainage flows. Except for a small cut the ravine mouth is blocked by low dunes; the resurvey measurement terminated at the lakeward crest of these dunes. To the north and south bluffs rise 43 to 50 feet and are composed of sand overlying till.

[d] Because of the rounded nature of the crest and pedestrian traffic the position of the bluff line is somewhat ambiguous.

[e] Although results of this survey indicated long-term net accretion comparison with a R.L.S. property survey indicated a bluff crest loss of 8.8 feet between 1974 and 1976.

[f] The resurvey measurement was carried to a line connecting the bluff crest on either side of the section line easement. The bluff at the easement was notched in 1973 when a drainage pipe was installed.

[g] At four dune sites (M23, M31, M36, and M53) two distinct bluff crests are recognized. The lakeward crest is a bluff line of a lower-relief dune terrace which fronts the more landward crest of a somewhat higher-relief dune feature. Because of the situation and the lack of clarity in the GLO notes it is not possible to positively ascertain to which point the GLO measurement terminated; consequently, this study's measurements were carried to each of the two possible crest lines and corresponding recession rates then determined. In the table the upper figure pertains to measurements to the crest line of the somewhat higher-relief landward dune form and the lower figure to measurements to the bluff

Table C2 (cont'd.).

line of the lower-relief lakeward dune feature. In three of the four cases measurements to either crest indicated relatively small change in bluff line position relative to the GLO surveys. The recession or accretion rates determined for the four sites are not included in any of the quantitative analysis performed in this study. In no way does this exclusion affect any of the conclusions reached and, in fact, their inclusion would only increase support for the findings reported.

[h] During the high lake period of the early 1950's the water level was up against the base of the present bluff. However, during the low lake stage in the late 1950's and early 1960's a foredune terrace three to nine feet in height and at least 65 to 75 feet in width had formed in front of the present bluff; this foredune has largely been removed by wave erosion during the present high water period.

[i] Although there has been only minor "recent" erosion at the bluff crest at the section line location, erosion has reached the crest several hundred feet to the north and south.

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