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Rates and Processes of Bluff Recession Along the Lake Michigan Shoreline in Illinois

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ABSTRACT. *We examined bluffs along 30 km of the Lake Michigan shoreline from Wilmette to Waukegan, Illinois, to measure amounts and variation in retreat rates and to determine what factors control rates and processes of retreat. The predominant bluff-retreat process is shallow- to intermediate-depth translational landsliding triggered by heavy rainfall and wave erosion at the base of the bluff; rotational slumping and shallow creep and earth flow also are common. Using historical maps and airphotos, we measured amounts of bluff-top retreat at 300 locations. For two time periods, 1872-1937 and 1937-1987, rates of retreat vary from 10 to 75 cm/yr between discrete segments of bluffs (defined by lithology) and between time periods for a given bluff segment. The average retreat rates for the entire area, however, do not vary significantly between the two time periods and are approximately 20-25 cm/yr. Long-term average and short-term extreme lake levels and precipitation also do not vary significantly between the two periods, and thus local temporal variations in retreat rate cannot be attributed to these factors. Shore protection built to date may have altered the spatial distribution of retreat rates in the area but has had little overall effect on the average regional retreat rates. The temporally constant regional retreat rates and the regular form of the local shoreline indicate that a long-term uniform rate of retreat prevails and that local variations in rates balance out through time to produce long-term parallel (in map view) bluff retreat in the area. This parallel bluff retreat probably is controlled primarily by the uniform retreat rate of the lithologically homogeneous shoreface in front of the bluff.*

INDEX WORDS: *Lake Michigan, Illinois, bluff retreat, shoreline processes, landslide, coastal erosion.*

INTRODUCTION

Record high levels of Lake Michigan in the mid-1980s created a period of increased shoreline erosion in the developed areas from Chicago to Waukegan, Illinois (Fig. 1). Much of this shoreline consists of steep bluffs that locally have responded to brief periods of high lake levels by retreating at accelerated rates. The recent period of increased retreat rates provoked concerns about the safety of structures along the shoreline. We studied bluff retreat in this area to determine what factors influence the processes and rates of bluff retreat, to measure and interpret spatial and temporal changes in those rates and processes, and to provide information that could be used by public officials, planners, and engineers.

In this paper, we address both the scientific and practical aspects of coastal bluff recession in Illinois. We begin by describing the physical setting of the bluffs; we then discuss the predominant processes of bluff retreat in the area. Next we describe a method for measuring bluff retreat; document the amount and rate of bluff retreat from 1872 to 1987 at 100-m intervals along the 30 km of shoreline studied; and measure rates of retreat for two subdivisions of this period, 1872-1937 and

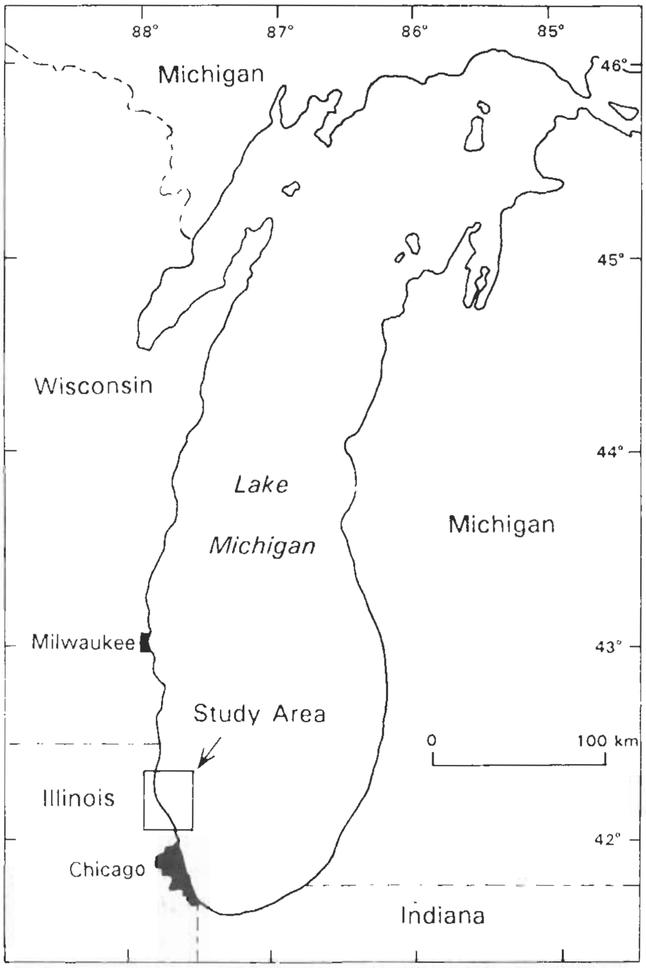

FIG. 1. Location map. Study area shown in Figure 2.

1937-1987, to measure temporal changes in retreat rates. We then relate observed temporal and spatial variations in retreat rates to temporal changes in lake level and precipitation and to spatial differences in bluff height, bluff lithology, and construction of shore-protective works to determine how these factors influence bluff retreat rates. Finally, we estimate the annual volume of sand and gravel, silt, and clay contributed to the littoral sediment transport system by bluff retreat.

GEOLOGY AND MORPHOLOGY OF THE BLUFFS

The bluffs consist of late Wisconsin glacial deposits, primarily till of the Lake Border morainic system (Willman 1971), which is a morphostratigraphic unit of the Wadsworth Till Member of the Wedron Formation (Frye *et al.* 1969, Willman and Frye 1970). Although Clark and Rudloff (1990) show that the Wadsworth Till Member includes a variety of glaciolacustrine deposits as well as till, we designate these deposits as till for brevity. Lacustrine sediment of the Equality Formation (Willman and Frye 1970) deposited in Glacial Lake Chicago (Clark and Rudloff 1990) locally overlies till of the Lake Border moraine system. From Waukegan to the Great Lakes Naval Training Center (Fig. 2), the bluffs are composed of silty clay till of the Zion City moraine interbedded with glaciolacustrine silt, sand, and gravel. From the Naval Training Center to Lake Forest, the bluffs consist of lacustrine silts, sands, and gravels overlying 3-4 m of till exposed at the base of the bluff. The Highland Park moraine, which is lithologically and geomorphically similar to the Zion City moraine, is exposed from Lake Forest to Winnetka. Between Winnetka and Wilmette, the bluff is only 5-10 m high and consists of interbedded lacustrine silt and gravel overlying about 2 m of till exposed at the base of the bluff. Figure 3 shows idealized cross sections of bluffs consisting of (A) till and (B) lacustrine sediment overlying till. Hereafter, bluffs composed of these two sediment types will be referred to as till bluffs and lacustrine bluffs, respectively.

The bluffs can be separated into two morphologically distinct reaches, whose boundary is defined by an abrupt doubling of the bluff height (Fig. 4) at the terminus of the Highland Park moraine (Fig. 2). The bluff formed by the southern outcrop of lacustrine deposits between Wilmette and Winnetka (segments 1-52), which we refer to as the low bluff, averages 8 m in height and has 15°-25° slopes. The bluff from Winnetka to Waukegan (segments 53-300), which we refer to as the high bluff, averages 19 m in height and has slopes from 25° to almost vertical. Figure 4 shows that the height of the till bluffs is highly variable, whereas the lacustrine bluffs have more consistent heights. The entire bluff supports a thick cover of deciduous trees and associated underbrush. Perched ground water commonly seeps from the bluff face along contacts between layers of contrasting permeability. Almost the entire length of the bluff has some sort of engineered shore protection, but type and quality vary substantially.

Land use along the bluffs is primarily moderate-density housing. Large, single-family homes on medium to large, well-landscaped lots are present along most of the bluff; parks, golf courses, and

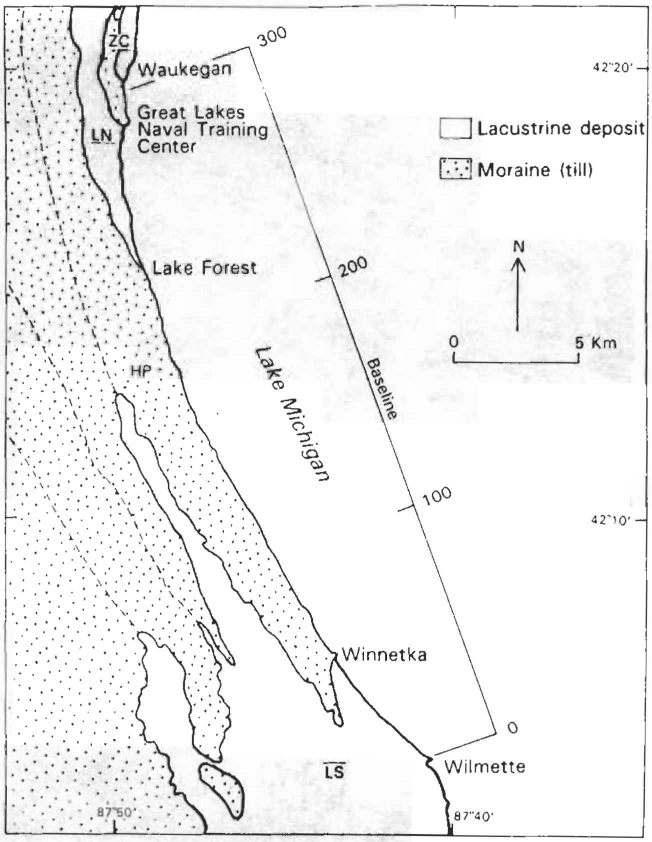

FIG. 2. ***Map showing the surficial geology of the study area (generalized from Willman and Lineback 1970). Baseline shows bluff segment numbers. Geologic units: LN, northern outcrop of lacustrine deposits; LS, southern outcrop of lacustrine deposits; HP, Highland Park moraine; ZC, Zion City moraine. Dashed contacts separate distinct moraines.***

cemeteries also are present. The primary effect of land-use variation along the bluffs would be on surface and ground water: roads and structures decrease ground-water infiltration (which would reduce the likelihood of landsliding) and increase surface runoff (which would enhance surface erosion). Because development and land use along the entire bluff are fairly uniform, the effect of land-use variation need not be considered in this study.

PROCESSES OF BLUFF RETREAT

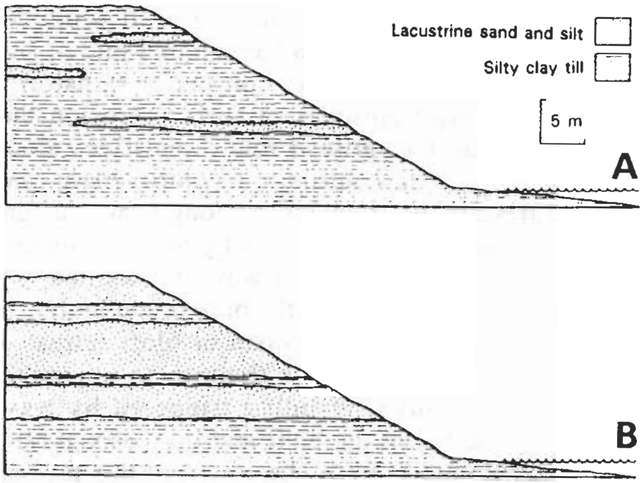

FIG. 3. ***Typical cross sections of bluffs in the study area. A, bluff in silty clay till; B, bluff in lacustrine sand and silt overlying till.***

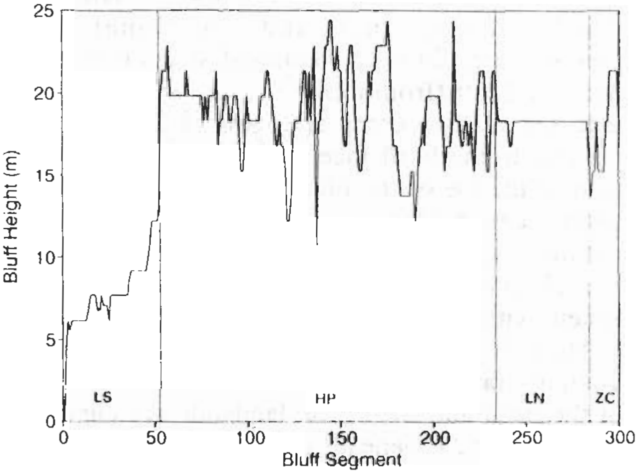

FIG. 4. ***Graph showing variation in bluff height in the study area. Vertical dashed lines show locations of contacts between till and lacustrine bluffs; abbreviations as in Figure 2.***

Retreat of shoreline bluffs (either lacustrine or oceanic) can result from a variety of processes that operate at different rates and that respond to different triggering mechanisms. For example, wave erosion is a primary cause of bluff retreat, and brief, intense storms that generate large wave surges can trigger very large amounts of bluff retreat in a matter of a few hours or days. Longer term basin-wide or eustatic increases in water level also can increase long-term rates of bluff erosion and recession by submerging beaches and exposing bluffs more directly to wave action (Vallejo and Degroot 1988). Surface erosion from runoff can contribute to bluff recession: runoff from normal rainfall produces what might be considered a background rate of surface erosion, and less common major rainstorms may trigger brief episodes of surface erosion that far exceed the background rate. Landslides along the bluffs likewise contribute to bluff retreat, and such slides can be triggered by long-term changes in ground-water conditions, brief periods of intense rainfall, rapid snowmelt, and wave erosion that undermines and oversteepens the base of the bluff.

The predominant mechanism of bluff retreat in the study area appears to be shallow- to intermediate-depth (0-5 m) landsliding triggered by wave erosion at the toe of the bluff and by seasonal rainfall. Several studies have characterized this process in detail for bluffs in Wisconsin, immediately north of our study area (Edil and Vallejo 1977, 1980; Edil and Haas 1980; Edil 1982; Bosscher *et al.* 1988; Edil and Bosscher 1988; Vallejo and Degroot 1988). The conclusions of these studies can be summarized as follows: (1) shallow- and intermediate-depth translational and rotational slides predominate, (2) deep rotational slides that involve the total bluff (from top to toe) are rare or nonexistent, (3) shallow creep and flow of surficial layers parallel to the bluff face is common, (4) wave erosion of the toe of the bluff triggers slope instability and influences slope morphology, and (5) landslides are most active in response to heavy spring rainfall. Our observations of bluff retreat in Illinois are consistent with these conclusions.

Most slope movement in the study area involves complex failure geometries where the slip surfaces at the head and toe of the landslide are curved and the slip surface beneath the main body of the slide is planar at a depth of about 0.5-3.0 m. Thick vegetation makes determining landslide activity and geometry difficult, particularly because predominantly translational slides cause little disturbance or tilting of trees (Fig. 5). Benched topography at the heads of slide masses are one indicator of slope instability. Also, forward rotation and toppling at the toe of the slope typically accompany translational movement in this area, so forward tilting of trees there can indicate slope movement. In most cases, the tills lose much of their shear strength as movement proceeds, and the slides transform into earth flows on the lower part of the slope (Fig. 6). Such flows have convex snouts and disaggregated internal structure. Rotational slides (slumps) are far less common; where they occur, backward rotation of landslide heads can be identified by backward tilting of trees (Fig. 7). Slumps also generally transform into flows as they move downslope. Several locations along the bluffs show evidence of older deep-seated slumping that involved most of the bluff face, but most such slumps appear not to have been active for perhaps several decades. Some slumps in the area have thicknesses as great as 15 m, as judged by the width of the head, but most are 2-5 m thick. Earth flow and creep of near-surface layers parallel to the slope face are common along much of the bluff and can occur in combination

FIG. 5. Translational slide along bluffs north of Lake Forest. Trees on the landslide block remained vertical, which indicates translation on a planar shear surface.

FIG. 6. Lower part of translational slide south of Lake Forest that has transformed into an earth flow. Note disruption of soil structure, forward tilting of trees, and convex slope profile in foreground.

FIG. 7. ***Rotational slump along bluffs near Lake Forest. Note backward rotation of trees on original ground surface of the slide block.***

FIG. 8. ***Slope experiencing creep and flow of surficial material. Trees are tilted chaotically; some have sinuous trunks.***

with deeper seated landsliding. Chaotic tilting of trees, hummocky topography, and bulging toes of slopes are common indicators of earth flow and creep (Fig. 8).

Till bluffs and lacustrine bluffs fail by similar landslide mechanisms. The coarser lacustrine material does tend to produce a slightly greater proportion of translational slides parallel to the slope face, and the finer grained till bluffs have a somewhat greater proportion of rotational failures. This is consistent with the behavior of the respective slope materials: sands and silts are predominantly frictional and tend to fail in an infinite-slope geometry (thin slabs parallel to the slope face with large length-to-width ratios); whereas, the shear strength of clays is dominated by cohesion, which generates curved, convex-upward failure surfaces that characterize slumps. This difference is subtle, however, and fairly thin translational slides predominate along both till and lacustrine bluffs, perhaps because weathered surface layers in clay till can become granulated and behave similarly to coarser grained materials.

Some parts of the bluff contain active landslides and obviously are currently retreating fairly rapidly by that mechanism. Other reaches of the bluff are covered by thick vegetation and appear to be stable. Close examination of such reaches, however, shows clear evidence of slope movement within at least the last several decades. Most of the low bluff has been graded and landscaped, so no record of previous landslide activity is preserved, but virtually the entire length of the high bluff shows evidence of historical activity. The thick vegetative cover provides a deceptive aura of stability, but most trees appear to be no older that 20-30 yr, and few, if any, are older than about 50 yr. Thus, even bluffs that appear intact and are covered by undisturbed trees may have been stable only for a few decades, and most such bluffs have benched topography and other features indicating fairly recent movement.

The width of the beach in front of the bluff appears to relate to the current state of landslide activity in many areas, presumably because wider beaches shield the bluff from direct wave attack. For example, the area south (downdrift) of the Highland Park water treatment plant has little or no beach and contains a long complex of active landslides. Trees near the base of the slope have toppled forward as the slides have transformed into flows and rotated forward. Sea walls, rip-rap, and other engineering works are being undermined by direct wave attack. Wide beaches are present north (updrift) of the plant, and bluffs there are currently relatively stable. However, even these bluffs show evidence of landslide activity within the last several decades, so their current stability may be ephemeral. Also, although many bluffs protected by wide beaches currently are stable with respect to translational and rotational sliding, they experience episodes of creep or flow of surficial layers.

RATES OF BLUFF RECESSION

Sorting out the relative effects of landsliding and other bluff-retreat processes and the rates at which they operate is a complex problem, and most research to date has focused on individual processes rather than on an integrated model. In terms of the effects of bluff recession on the public, however, the intricacies of the interaction of several processes and their varying rates is perhaps less important than the net effect over a given time period. Thus, the critical issue in terms of human planning is how far a given part of the bluff will recede in a relevant time period; for long-term human planning, time periods of 50-100 yr generally are of greatest interest.

Several studies of bluff retreat rates along other Great Lakes shorelines have been reported (e.g., Carter 1976, Kilgour *et al.* 1976, Quigley and Di Nardo 1980), and a detailed study similar to ours was conducted for Milwaukee County, Wisconsin, just north of our study area (Southeastern Wisconsin Regional Planning Commission 1989). Little has been published on bluff recession along the Illinois shore, however. Berg and Collinson (1976) and Lineback (1974) used maps and airphotos to determine rates of bluff-top retreat along 21 profiles for periods of a few years to more than 100 yr, and they compared rates in different areas. Larsen (1973) modeled bluff recession as a function of shoreline retreat at 26 evenly spaced locations between Waukegan and Wilmette to estimate spatial and temporal rate changes. These studies provide regional estimates or single-point measurements of retreat rates along the Illinois shoreline or analogous rate measurements from other Great Lakes shorelines with which we can compare our results. None, however, has involved a comprehensive documentation and interpretation of retreat rates along this shoreline over the time period of interest. More recently, we (Jibson *et al.* 1990; Jibson and Staude 1991, 1992) have conducted studies of bluff retreat rates along the Illinois shoreline, the results of which we discuss below.

Measuring Bluff Recession and Calculating Recession Rates

We divided the 30 km of bluffs from the north side of Wilmette harbor to the north side of the Great Lakes Naval Training Center into 300 segments, each 100 m long. Segments were defined by projecting perpendicular lines from a baseline bearing N. 20° W. and were numbered from south to north (Fig. 2). Data on bluff recession, bluff height, lithology, and the presence of shore-protective works were collected for each bluff segment. A limitation of using equal segment lengths is that some segments may straddle boundaries between areas of differing geologic, geomorphic, or engineering characteristics that may affect bluff recession, but the short segment length of 100 m minimizes this problem.

We used a common technique (e.g., Stafford and Langfelder 1971, Williams *et al.* 1979) of documenting bluff retreat by comparing bluff positions on historical maps and airphotos of different ages. Our density of measurements, however, is much greater than in most previous studies and thus provides an extensive database for analysis. We compared bluff positions from three data sources: 1:20,000-scale topographic maps made in 1872 by the U.S. Army Corps of Engineers (earliest maps at a usable scale), 1:14,400-scale airphotos taken in 1936 (earliest airphotos), and 1:14,400-scale airphotos taken in 1987 (most recent airphotos). The best method to document changes in bluff position is to measure the distance from the upper edge of the bluff to a reference feature. A recognizable feature on all data sources is the Chicago and Northwestern railroad grade, which roughly parallels the shoreline in the area. On the 1872 maps, we plotted the baseline, segmented the bluff, and measured the distance perpendicular to the baseline from the upper bluff edge to the center of the railroad grade at the midpoint of each segment. On the airphotos, we used a zoom-transfer scope to trace the position of the bluff edge onto U.S. Geological Survey topographic base maps (Evanston, Highland Park, and Waukegan $7^1/_2$' quadrangles) enlarged to 1:12,000 scale. We plotted the baseline and bluff segments on the maps and measured the distance to the railroad grade for each segment. Bluff recession at each segment was calculated by comparing the distances between each pair of data sources. Thus, we derived recession records for the 115-yr period from 1872 to 1987, the 65-yr period from 1872 to 1937, and the 50-yr period from 1937 to 1987.

Primary sources of location error include inherent airphoto distortion and imperfect registration of the map and airphoto on the zoom-transfer scope. Based on the scale and resolution of the airphotos and on measured registration inconsistencies on the zoom-transfer scope, we estimate that the combined location error from all sources for single features plotted from airphotos does not exceed 3 m; thus, distances measured between any two features are accurate within 6 m, and comparisons of two such distances are accurate within 12 m. Measurements directly from the 1872 maps are estimated to be accurate within 5 m; comparisons with measurements from airphotos are thus accurate within 11 m. If location errors are random, they should have little net effect on regional averages calculated from the large data base.

Amounts of Recession and Recession Rates

From 1872 to 1987 the average amount of recession for all bluff segments was 29 m; the maximum for any segment was 155 m. Average amounts of recession for the 1872-1937 and 1937-1987 periods were 20 m and 11 m, respectively; maximum amounts were 130 m and 85 m. These amounts of recession are large in view of the fairly dense development along most of the shoreline. To compare bluff retreat across different time intervals, we divided the amounts of retreat by the durations of the time periods to obtain the annual retreat rate.

Figure 9 shows annual retreat rates for the three time periods for the 300 bluff segments. Significant spatial variation in retreat rates appears related to contrasts between till and lacustrine bluffs. In the 1872-1987 and 1872-1937 periods (Figs. 9A and 9B), retreat rates of the lacustrine bluffs are much greater than the retreat rates of the till bluffs. Temporal variations are apparent between the 1872-1937 and 1937-1987 retreat rates (Figs. 9B and 9C). The 1872-1937 rates vary markedly between till and lacustrine bluffs, and local areas of high retreat rates are interspersed between areas of little or no retreat. In contrast, the 1937-1987 rates are more uniform throughout the area.

The rather spiky appearance of Figure 9 indicates that bluff segments having high retreat rates are adjacent to segments having much lower rates; thus, a highly irregular shoreline is expected. Viewed at regional scale, the shoreline appears quite regular (Fig. 2); but viewed at large scale (Fig. 10), local shoreline irregularities have sizes consistent with the differences in retreat rates shown in Figure 9.

Table 1 records mean recession rates for each time period and each section of bluff and changes in mean rates between periods; overall retreat rates for the entire bluff and rates for the low and high bluff also are shown. Retreat rates for the entire area are 20-30 cm/yr. Rates for individual sections of the bluff, however, define a much broader range, from 10 to 75 cm/yr. For each time period, the spatial rate variation relates to the lithology exposed. For 1872-1987, the two reaches where lacustrine sediment is exposed (LS and LN) have almost identical retreat rates that are much higher than the rates in the two till areas (HP and ZC). The 1872-1937 data show a similar rate contrast between lithologic types. In 1937-1987, the two till areas have almost identical rates, but the two lacustrine areas differ markedly from the till areas and from each other.

Figure 9D shows changes in retreat rates between the two time periods; positive values indicate a rate increase from the early to the late period. The lithologic control is striking. The rate-change data in Table 1 show that the lacustrine bluffs had much higher retreat rates from 1872 to 1937 than from 1937 to 1987 and that the till bluffs either had little change (ZC) or much higher rates (HP) in the later period. Interestingly, most local areas experienced large rate changes of as much as 120 percent, but, because some changes were positive and others negative, the net rate change for the entire area was rather modest—a 27 percent decrease.

Retreat rates for the low bluff (Table 1) decreased dramatically from 73.2 cm/yr in the early period to only 12.7 cm/yr in the late period. In contrast, rates for the high bluff vary only slightly between time intervals: the rate for 1872-1937 is 21.6 cm/yr, and for 1937-1987 it is 24.2 cm/yr. This difference of roughly 10 percent is insignificant as compared to the range of possible error in the method. Local rates along the high bluff vary considerably between till and lacustrine bluffs, however. For example, in the till bluffs along the Highland Park moraine, the retreat rate more than doubled from the early to the late period; just to the north along the northern lacustrine bluffs, the retreat rate was halved.

Factors Affecting Rate of Bluff Retreat

What causes the observed spatial and temporal variation in retreat rates along the bluffs? In this section, we examine and analyze how temporal variation in lake level and precipitation and spatial variation in bluff height, bluff lithology, and shore-protective works might affect bluff-retreat rates.

Temporal Changes in Lake Level. Change in lake level commonly is considered to be the major factor that controls changes in bluff retreat (e.g, Carter 1976, Vallejo and Degroot 1988). Short-term high stands of Lake Michigan generally lasting a few years have caused brief periods of increased bluff retreat (Lineback 1974, Berg and Collinson 1976, Vallejo and Degroot 1988). Gradual, long-term

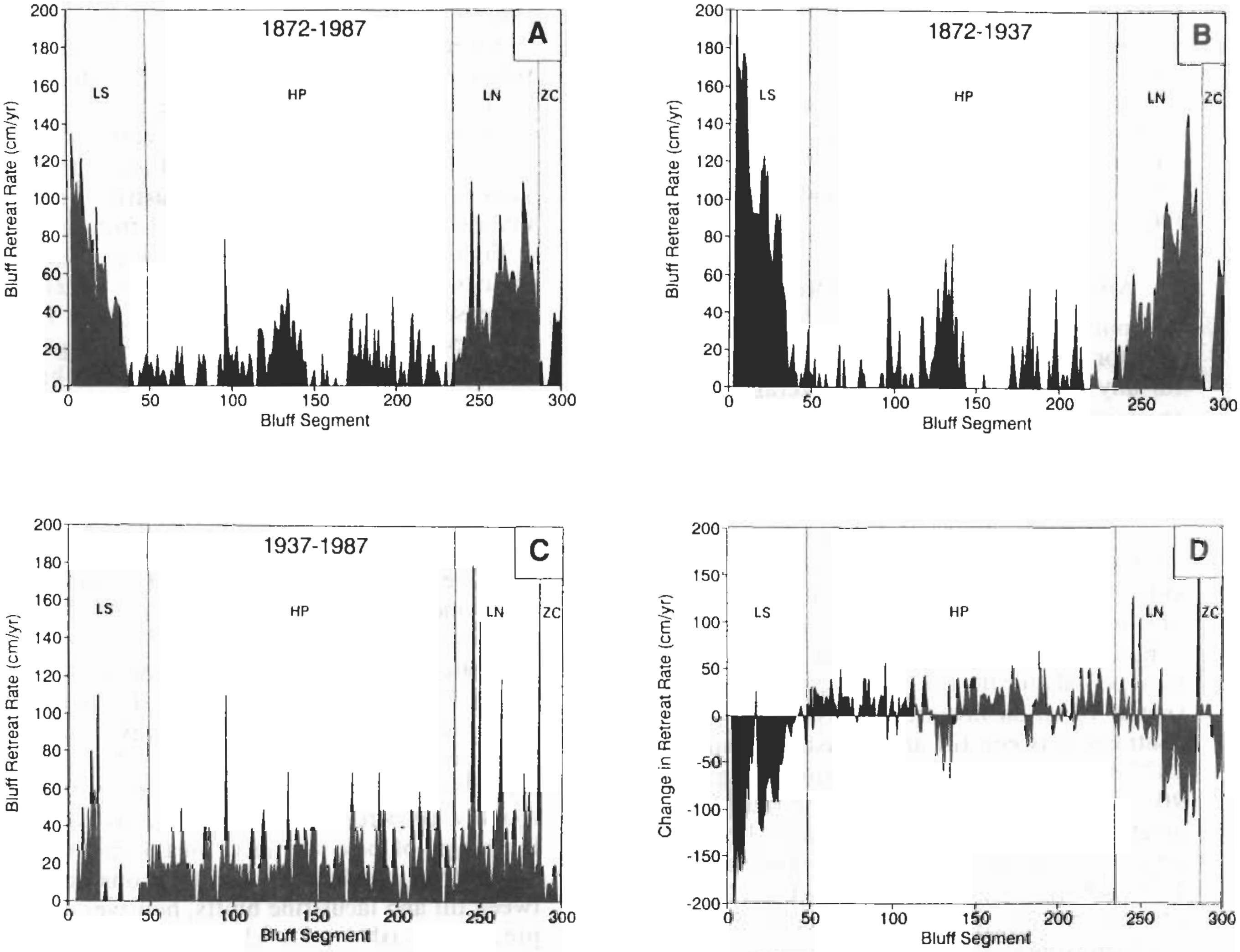

FIG. 9. Annual rates and changes in rates of bluff retreat between Wilmette and Waukegan; bluff segment numbers correspond to baseline in Figure 2. A, retreat rates for 1872-1987; B, retreat rates for 1872-1937; C, retreat rates for 1937-1987; D, changes in retreat rates between 1872-1937 and 1937-1987 (positive values where rate is greater in the later period). Vertical dashed lines show locations of geologic contacts; abbreviations as in Figure 2.

(decades to centuries) changes in lake level also affect bluff retreat according to most models of bluff-retreat mechanisms (e.g., Edil and Vallejo 1980, Vallejo and Degroot 1988). Because we are interested in time periods of 50-100 yr (relevant for human planning purposes), we measured some parameters of lake-level change between the 1872-1937 and 1937-1987 periods to detect (1) gradual changes in average lake levels and (2) differences in short-term extreme (maximum and minimum) lake levels.

We analyzed monthly and annual average lake-level data from the National Oceanic and Atmospheric Administration (no date); these data are derived from hourly and daily lake levels and thus implicitly account for durations as well as elevations of lake levels. We calculated the arithmetic mean, standard deviation, maximum, minimum, and total range of average annual lake levels for both time periods. We also calculated the percentage difference between various statistical measures for the data from the two time periods, and we used a statistical *t*-test to calculate the probability that the lake levels for the two time periods are statistically identical. To analyze extreme events, we determined the maximum and minimum monthly lake

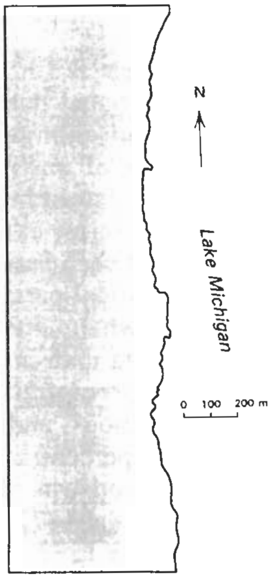

FIG. 10. Large-scale map showing the position of the upper edge of a part of the bluff south of Great Lakes Naval Training Center. Irregularities in the bluffline at this scale are consistent with rate variations between adjacent bluff segments shown in Figure 9.

levels for each year and determined statistical parameters for these data sets as described for average annual precipitation.

Table 2 shows that average annual lake levels for the two periods are remarkably similar: the total range in average annual lake level for both periods is 5.42 ft (1.65 m), and the difference in the means for the two time periods is only 0.01 ft (0.31 cm), or 0.1 percent. Maximum and minimum values of average annual lake level and the standard deviations all differ by less than 5 percent. Maximum and minimum monthly lake-level data likewise show remarkable similarity between the two periods. For all three pairs of data sets, the *t*-tests show that the data from the two time periods are statistically identical.

The data show no significant differences in average lake levels between the two periods that would indicate gradual, long-term changes in lake level. The similarity between the standard deviations for the two periods shows that variation about the means also was consistent between periods. The data also show no significant differences in maximum or minimum lake levels that would indicate differences in the number or magnitude of extreme lake-level events between the two periods. Therefore, *at this time scale*, local temporal changes in bluff retreat rates cannot be attributed to lake-level

TABLE 1. Bluff recession data.

	Recession Rate			Rate Change		Groins as of 1955	
Bluff Section (segments)	1872-1987 (cm/yr)	1872-1937 (cm/yr)	1937-1987 (cm/yr)	(cm/yr)	(%)	Number	Density (#/km)
LS (1-52)	46.8	73.2	12.7	-60.5	-82.7	9	1.7
HP (53-233)	13.2	10.2	22.6	12.4	121.6	64	3.5
LN (234-284)	45.8	59.2	30.4	-28.8	-48.6	26	5.1
ZC (285-300)	22.0	24.6	22.0	-2.6	-10.6	12	7.5
Low Bluff (1-52)	46.8	73.2	12.7	-60.5	-82.7	9	1.7
High Bluff (53-300)	20.9	21.6	24.2	2.6	12.0	102	4.1
Total Bluff (1-300)	25.4	30.5	22.3	-8.2	26.9	111	3.7

Note: LS, southern exposure of lacustrine deposits; HP, Highland Park moraine; LN, northern exposure of lacustrine deposits; ZC, Zion City moraine. Rate change is calculated by subtracting the 1872-1937 recession rate from the 1937-1987 rate.

fluctuations. This is not to say that changes in lake level do not affect retreat rates at any time scale, but rather that because lake-level fluctuation was virtually identical for both observed time intervals, it could not have caused differences in retreat rates between those intervals. Lake level certainly changes over shorter (days to years) and longer (several centuries or millennia) durations, but the time periods examined are appropriate for long-term planning in human terms.

Temporal Changes in Precipitation. Precipitation can affect bluff stability in several ways. In addition to affecting lake levels, precipitation also affects local ground-water conditions and surface runoff. Brief (hours to days), intense storms as well as longer periods (months to years) of increased rainfall probably affect bluff retreat rates, though possibly in different ways. We compared average annual and maximum monthly data for the two time periods in the same manner as for the lake-level data. Analysis of average annual data enables detection of gradual, long-term changes in precipitation amounts, and analysis of maximum monthly data provides an index to determine if the number or magnitude of shorter term, extreme precipitation events has changed between periods.

Table 2 shows statistical parameters for the databases analyzed. Somewhat more variation is present in the precipitation data than in the lake-level data. For average annual precipitation, differences in means, standard deviations, and ranges for the two periods differ by 8-16 percent; average precipitation in the 1937-1987 period was slightly greater and more variable than for the 1872-1937 period. The *t*-test probability that the 1872-1937 and 1937-1987 populations for average annual precipitation are identical is only 0.07, much lower than the probabilities for the lake-level data; however, a probabil-

TABLE 2. Changes in lake level and precipitation.

	Mean	Standard Deviation	P	Maximum Value	Minimum Value	Range
Average Annual Lake Elevation (ft)						
1872-1937	578.56	1.23		580.94	575.84	5.10
1937-1987	578.57	1.27	0.99	581.18	575.76	5.42
% Difference	0.1	3.2		4.4	1.5	5.9
Maximum Monthly Lake Elevation (ft)						
1872-1937	579.14	1.28		581.55	576.21	5.34
1937-1987	579.12	1.32	0.94	581.89	576.15	5.74
% Difference	0.3	2.9		5.9	1.1	7.0
Minimum Monthly Lake Elevation (ft)						
1872-1937	577.87	1.20		580.15	575.40	4.75
1937-1987	577.82	1.29	0.83	580.62	575.42	5.20
% Difference	1.0	6.9		9.0	0.4	8.6
Average Annual Precipitation (in)						
1872-1937	32.91	5.42		45.86	22.78	23.08
1937-1987	34.95	6.48	0.07	46.96	21.19	25.77
% Difference	7.9	16.4		4.3	6.2	10.4
Maximum Monthly Precipitation (in)						
1872-1937	5.89	1.68		11.28	2.82	8.46
1937-1987	6.31	1.75	0.20	11.69	3.33	8.36
% Difference	4.7	4.0		4.6	5.8	1.2

Note: P is the probability that the two populations (1872-1937 and 1937-1987) are statistically identical. Elevations are in feet (1 ft = 0.305 m); datum is 1955 International Great Lakes Datum. Precipitation is in inches (1 in = 2.54 cm).

ity of 0.07 still indicates that the hypothesis that the populations are significantly *different* is rejected at the 93 percent confidence level. A difference of less than 8 percent in mean annual precipitation probably is not enough to significantly affect bluff retreat processes and rates. Extreme values of average annual precipitation in these periods show even less variability than mean values. Minimum and maximum annual precipitation for the two periods differ by only 6.2 and 4.3 percent, respectively. Thus, as with lake levels, the differences in annual precipitation between the two periods is small enough that changes in bluff retreat rates cannot be attributed to changes in annual precipitation for the time interval analyzed.

Data for maximum monthly precipitation for a given year show even less variation: the means, standard deviations, and maximum values all differ by less than 5 percent between time periods, and the total ranges of the two data sets differ by only 1.2 percent. The *t*-test probability is 0.20; thus the hypothesis that the populations differ significantly is rejected at the 80 percent confidence level. Therefore, we detect no significant differences in extreme levels of monthly precipitation that would indicate variability in short-term extreme precipitation conditions between time periods that could significantly affect bluff retreat rates.

Bluff Height. Bluff height might be expected to influence retreat rates for at least two reasons, which have opposite effects. First, bluff height directly affects the stability of the bluff with respect to landsliding; all other factors being equal, increasing bluff height corresponds to decreasing slope stability (Edil and Vallejo 1980). Therefore, higher bluffs should be more susceptible to retreat from landsliding. Second, bluff height determines the volume of material that must be removed for a given amount of bluff retreat; thus, higher bluffs lose greater volumes of material per unit amount of retreat, and this greater amount of material requires more energy to remove it from the base of the bluff. In this case, higher bluffs correspond to lower retreat rates.

Figure 4 shows variation in bluff height along the shoreline; the high and low bluffs are distinct, but variation within the high- and low-bluff areas also is significant. We constructed two linear regression models, one for 1872-1937 and one for 1937-1987, to measure correlation between bluff height and retreat rate. In each model, we regressed the bluff height at each 100-m segment against the retreat rate for that segment. The model for 1872-1937 has an R^2 value of 27 percent and a high level (greater than 99 percent) of statistical significance, which indicates that for the early time period, a small but significant amount of the variation in retreat rates is explainable by variation in bluff height. The correlation is negative, that is, high retreat rates correlate with low bluff height. Figure 9 clearly shows that in the early period, the southern lacustrine bluffs, which have low bluffs, had very high rates of retreat, and this is reflected in the regression model.

The regression model for 1937-1987 has an R^2 value of only 2 percent and a low level (less than 95 percent) of statistical significance, and the regression model shows an opposite (positive) sense of correlation as compared to the regression model for the early period. Therefore, for the later period, we detect no significant correlation between bluff height and retreat rates. Thus, whatever influence low bluff height may have had on increasing retreat rates in the early period is not present in the later period.

The reason for the negative correlation between bluff height and retreat rate for the early period and the lack of correlation for the late period is not entirely clear. One possible reason may be the influence of Wilmette Harbor at the southern end of the area (Fig. 2). At present, Wilmette Harbor is a sediment barrier that has impounded large amounts of sand and created wide updrift beaches to the north that protect much of the low bluff from wave attack. Wilmette Harbor was constructed in 1910, so during much of the early period the low bluff immediately north of the harbor probably had much narrower fronting beaches and less protection from wave attack than at present. If lower bluffs retreat more rapidly than higher bluffs when subject to wave attack because less material must be removed, this difference in beach width between early and late periods could explain the results of the regression models.

Bluff Lithology. As discussed above, bluff lithology relates closely to spatial differences in retreat rates (see Fig. 9). Lithologic differences between different reaches of bluffs are primarily confined to the upper part of the bluff, which is subject to wave attack only in the most extreme conditions. The lacustrine deposits lie on silty clay tills exposed at the base of the bluff (Fig. 3). Therefore, differences in retreat rates between lithologically distinct parts of the bluffs must relate primarily to processes that affect the upper part of the bluff, such as landsliding and rainfall-induced surface erosion, which are not controlled solely by wave attack.

Lacustrine bluffs, composed primarily of sand and silt, have greater retreat rates than till bluffs in all time periods and areas but one, the southern lacustrine bluff from 1937 to 1987. The sand and silt lack significant cohesive strength, which may render lacustrine bluffs more susceptible to surface erosion during rainstorms (Lineback 1974) and to wave attack during rare extreme events. Also, the sand and silt layers conduct ground water to the bluff face, where seeps are common. Interbedded clayey till layers create perched water tables and confine some permeable silt and sand layers causing buildup of high pore-water pressures; both the perched and confined ground-water conditions contribute to landsliding along the bluff (Hadley 1976, Mickelson *et al.* 1977, Edil and Vallejo 1980, Sterrett and Edil 1982, Edil and Bosscher 1988). Our observations indicate that the northern lacustrine bluffs contain the greatest concentration of landslides in the area.

The fine-grained till bluffs have a significant component of cohesive strength, which imparts greater overall shear strength to the till bluffs as compared to the lacustrine bluffs (DuMontelle *et al.* 1976). Although the clay till probably resists wave attack more effectively than lacustrine silt and sand, the till also is susceptible to deeper seated landsliding. Landslides are abundant along the bluffs of the Highland Park moraine, and, when they occur, they shift the location of the upper edge of the bluff by a large amount almost instantly.

The extreme rates of retreat and changes in retreat rates along the southern lacustrine bluffs probably are better explained by the distinct difference in bluff height there than by lithologic differences. As discussed previously, retreat of the low bluff may have occurred rapidly prior to construction of Wilmette Harbor, which created a sediment barrier that substantially widened the fronting beaches in much of the low bluff area.

If the lower retreat rates of till bluffs as compared to lacustrine bluffs were to persist, the till bluffs would become headlands and the lacustrine bluffs would recede to become reentrants: an irregular coastline would develop. Although local irregularities have developed (Fig. 10), the southwestern Lake Michigan shoreline is very regular and broadly arcuate, and the shape and character of the shoreline do not change abruptly at lithologic boundaries (Fig. 2). Rate variations since 1872 between till and lacustrine bluffs do not explain the observed geomorphology of the bluffline and thus must not persist for long periods of time. Therefore, retreat rates of bluffs composed of different materials must vary in time to produce parallel (in map view) bluff retreat on a regional scale. For example, the more than doubling of the retreat rate along the Highland Park moraine between the early and late periods corresponds in time with substantial reductions in retreat rates in adjacent lacustrine bluffs (Table 1). The 115-yr observation period is too brief to unequivocally document this phenomenon, but the regular coastline strongly supports a model of long-term parallel bluff retreat in the area.

Shore-Protective Works. Almost the entire length of the shoreline along the bluffs currently has some type of artificial shore protection. Types of protective works include groins, sea walls, revetments, rip-rap, and breakwaters, all of which vary in size, age, and quality of construction. Virtually all of the shore-protective works now present along the shoreline have been built since about the late 1920s; before then, fewer shore-protective works existed along the bluffs, and some reaches were entirely unprotected. Thus, during most of the early time period, the bluff retreated in a less protected state relative to the later period, in which a wider variety, higher density, and better quality of shore-protective works were present. Surprisingly, data from Table 1 show that the overall rate of retreat along the bluffs has not changed significantly; in fact, the retreat along the high bluff has actually increased slightly. The only exception, the reduction in retreat rate along the low bluff, probably relates to the construction of Wilmette Harbor, the largest sediment barrier south of the Great Lakes Naval Training Center. At this simplistic level of analysis, we could conclude that the shore-protective works built since the early part of this century have had little or no impact on the regional rates of bluff retreat. Figure 9 shows that the spatial distribution of retreat rates does differ between time periods. Figure 9B (1872-1937) shows several distinct areas of high retreat rates and intervening areas of little or no retreat; Figure 9C (1937-1987) shows a more even spatial distribution of rates. Therefore, construction of shore protection since the 1930s may have changed the spatial distribution of retreat rates, even if it did not affect the overall regional rate.

A report by the Illinois Division of Waterways (1958) provides a good database to more closely examine the effects of one type of shoreline protection—groins. Groins are vertical barriers, extending from the beach offshore, designed to trap sediment moving along shore and thus to widen beaches and protect bluffs from wave attack. Beginning in the late 1920s, an ambitious groin-building program began along much of the shoreline. Although many of these groins were built to replace an earlier generation of deteriorated rock piers (C.W. Shabica, Northeastern Illinois University, written commun., 1992), the Illinois Division of Waterways (1958) indicates a substantial increase in the number of shoreline structures dating from the 1920s and 1930s. By the late 1930s, many groins were in place, and this episode of groin construction continued into the 1950s. Most groins constructed along the bluffs during this period were of fairly consistent size and type (Illinois Division of Waterways 1958). Thus, comparing retreat rates along different parts of the bluffs between the two periods should provide insight for evaluating the effects of a substantial increase in the number and density of shore-protective structures on retarding bluff recession.

We used Larsen's (1973) compilation of the data from the Illinois Division of Waterways (1958) on the number and distribution of groins in the area built between 1872 and 1955. About 95 percent of these groins were built after 1920. Table 1 records the numbers of groins built by 1955 along each section of bluff and their density (number of groins per kilometer). The data show that these groins had no consistent effect on bluff retreat rate. The area having the greatest groin density (ZC) had a negligible change in retreat rate. The area having the lowest groin density (LS) experienced an 80-percent *reduction* in retreat rate, while the rate along the Highland Park moraine, which had twice the groin density, more than doubled. Along the high bluff, which contains 92 percent of the groins and has a high groin density, the retreat rate actually increased slightly; whereas, along the low bluff, which has a much lower groin density, the retreat rate decreased by more than 60 percent. Thus, construction of this early generation of groins neither enhanced nor degraded bluff stability in a consistent manner. The evening out of the spatial distribution of bluff retreat rates in the later period, therefore, probably cannot be attributed to this generation of groins.

The observations of the effects of shore-protective works on bluff retreat rates indicate that (1) shore-protective works may have created a more uniform spatial distribution of bluff retreat rates in the later period, but (2) these engineered works had little, if any, effect on the overall regional rate of bluff retreat. These conclusions probably do not apply to shore protection built in the last few years, which has not been in place long enough to have had a significant effect on retreat rates in the later period.

SEDIMENT VOLUME PRODUCED BY BLUFF RETREAT

One of the geologic effects of bluff retreat is the addition of sediment to the littoral transport system along the Lake Michigan shoreline. Availability, distribution, and movement of sediment along shore significantly affects shoreline geologic processes as well as human planning. Therefore, we used the bluff retreat rates, in conjunction with data on bluff geometry and sediment grain-size distribution, to estimate the volume of sediment contributed to the littoral system by bluff recession.

We conducted cone-penetration tests (CPT) at 10 sites in the study area. CPT involves pushing a conically tipped steel rod having a cross-sectional area of 15 cm^2 into the ground. Strain gages in the rod measure the load on the tip of the probe as well as the friction along the lateral edge (sleeve) of the probe. Published correlations between values of tip and sleeve resistance allow interpretation of the grain size of the material through which the cone is pushed (Meigh 1987). Because CPT grain size is interpreted by soil behavior rather than by direct measurement of particle size, boundaries between grain-size classes are qualitative.

We located penetrometer soundings within 15 m of the edge of the bluff; soundings extended to a depth below the base of the bluff (below lake level) in most cases. CPT grain-size data confirmed our general stratigraphic model (see Fig. 3) of the bluffs, but many additional sediment layers as thin as about 2.5 cm (the practical resolution of the CPT) were detected. For each CPT log, we estimated the amount of sand and gravel (grouped together), silt, and clay as a proportion of the total bluff height. We then linearly interpolated these proportions between each CPT log to construct a model of grain-size distribution for each 100-m bluff segment in the area (Fig. 11). Clearly, clay predominates the system; even including bluffs capped by lacustrine sediment, clay makes up 40-70 percent of the total throughout the area. The silt portion is remarkably constant at about 20 percent of the total, and the sand portion varies from 10-15 percent in till bluffs to 30-40 percent in bluffs

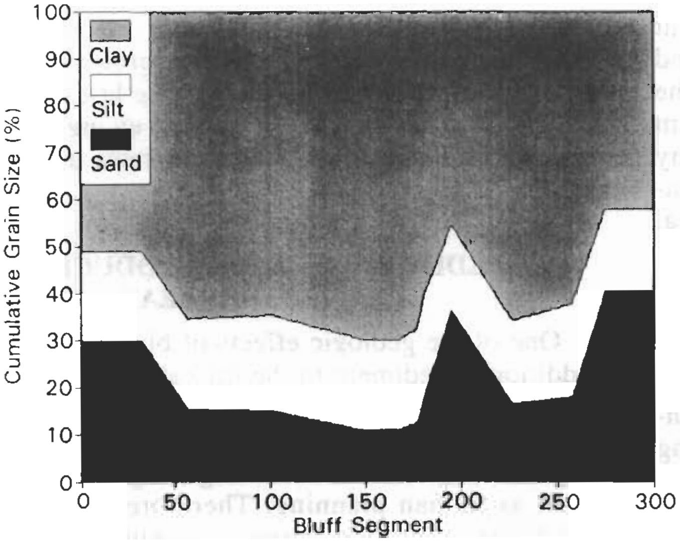

FIG. 11. Model of grain-size distribution along the bluffs derived by interpolating between 10 cone-penetration test sites spaced roughly uniformly along the bluff.

capped by lacustrine sediment. Grain-size distributions interpreted from CPT data are consistent with published grain-size data from laboratory analysis of drill samples of bluff materials in the study area (DuMontelle *et al.* 1976).

We estimated annual volumetric loss from the bluffs by assuming parallel cross-sectional bluff retreat. In this way, the volume of material removed annually from each bluff segment can be calculated by multiplying the bluff height (in meters) by the segment length (100 m) by the retreat rate (in meters/year). We applied the regional average retreat rate to all bluff segments because of the great local temporal variation in rates and because the average regional rate represents long-term conditions; both the 115-yr (1872-1987) rate and the most recent 50-yr (1937-1987) rate were used for comparison. The total volume per segment was then multiplied by the sediment grain-size proportions for each segment to yield an estimate of sediment volume by segment and by grain size for the entire study area (Fig. 12). Finally, we summed the respective annualized volumes of sand and gravel, silt, and clay for the entire area; we also divided these volumes by the total bluff length (30 km) to determine sediment volume per unit bluff length (Table 3).

Clay and silt normally are removed from the littoral system because they are carried in suspension away from the shoreline and settle offshore in deeper water. Therefore, the sand volume is of greatest interest for the near-shore environment. The two retreat rates used yield annual sand volumes of 23,000-32,000 m^3 over the entire 30 km of bluff, which averages out to about 1 m^3 of sand per linear meter of bluff (Table 3).

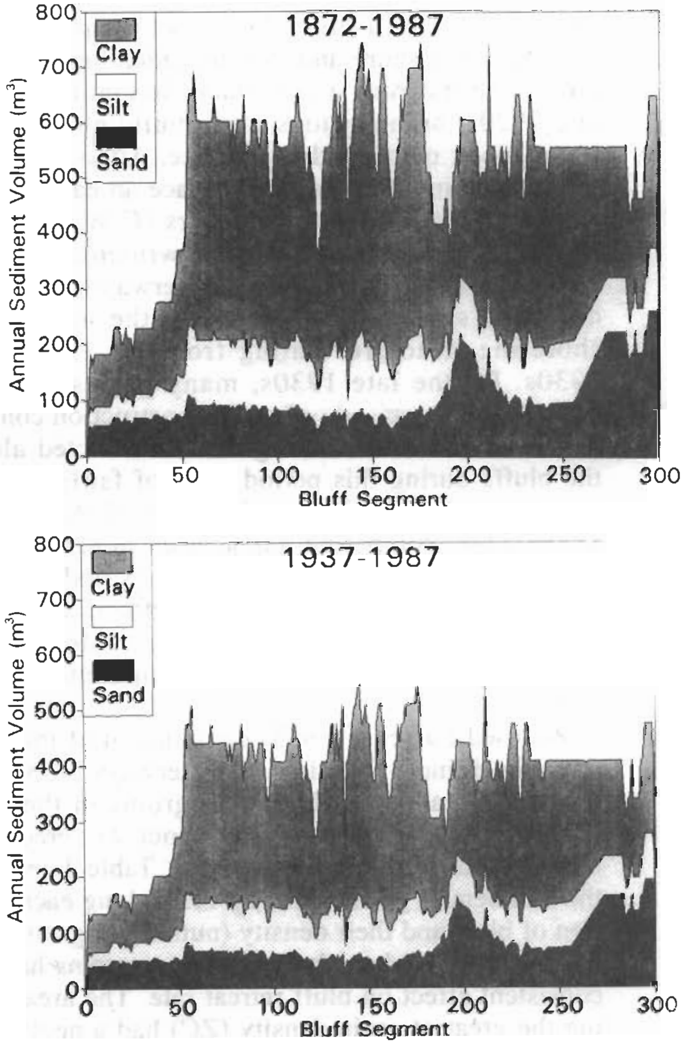

FIG. 12. Model of annual sediment volume (by grain-size class) caused by bluff retreat in the study area. A, volumes calculated using 1872-1987 average regional retreat rate; B, volumes calculated using 1937-1987 average regional retreat rate.

DISCUSSION AND CONCLUSIONS

Retreat rates from our study are similar to those from previous studies of this area (Larsen 1973,

TABLE 3. Sediment volume from bluff retreat.

Grain Size	1872-1987 Rate Volume (m³/yr)	1872-1987 Rate Volume/Length (m³/m/yr)	1937-1987 Rate Volume (m³/yr)	1937-1987 Rate Volume/Length (m³/m/yr)
Sand and Gravel	31,892	1.06	23,317	0.78
Silt	29,105	0.97	21,280	0.71
Clay	92,599	3.09	67,703	2.26
Total	153,596	5.12	112,300	3.74

Lineback 1974, Berg and Collinson 1976). A detailed study of bluff recession between 1963 and 1985 along about 50 km of bluffs in Milwaukee County, Wisconsin, just north of our study area, indicates that bluff recession rates range from less than 15 cm/yr to almost 400 cm/yr; the weighted average over the entire area is about 30 cm/yr (Southwestern Wisconsin Regional Planning Commission 1989), only slightly greater than rates along the Illinois bluffs. Published recession rates for other Great Lakes shorelines composed of similar lithologic units are significantly greater than our rates; for example, long-term (100-150 yr) average rates of 50-280 cm/yr have been documented for several reaches of the Lake Erie shoreline (Carter 1976, Kilgour *et al.* 1976, Quigley *et al.* 1977, Quigley and Di Nardo 1980). Lithologically similar bluffs in some areas along oceanic coastlines retreat by mechanisms similar to those operating along Great Lakes bluffs, so comparisons with rates there also is of interest. Recession rates along coastal till bluffs in the British Isles are much greater than along the Lake Michigan bluffs in Illinois: rates along part of the Northern Ireland coast are 21-84 cm/yr (McGreal 1979), and rates in southern England are 25-510 cm/yr (Barton and Coles 1984, Hutchinson 1973). Lower retreat rates along Lake Michigan compared to oceanic bluffs are not surprising because of the greater wave energy along oceanic coasts.

Our results regarding the influence of various factors on retreat rates appear at odds with some conclusions of previous studies as well as with intuition. Changes in bluff retreat rates commonly have been expected to correlate with fluctuations in lake level, and over brief time intervals (a few years) they have been shown to do so (e.g., Berg and Collinson 1976, Carter 1976, Quigley *et al.* 1977, Quigley and Di Nardo 1980, Vallejo and Degroot 1988). Over time periods of several decades, however, which are of greatest interest for human planning, average lake levels and the amount of variation in lake levels are constant, and extreme events that trigger short-term catastrophic bluff retreat appear to occur with the same magnitude and frequency over these time periods. Because no long-term variation in average or extreme lake-levels can be detected, lake-level fluctuations in the next 50-100 yr probably will be similar to those of the past 50-100 yr. The same conclusions apply to precipitation levels.

The fairly uniform regional retreat rates between the early period of less shoreline engineering and the late period of more intensive shoreline engineering indicate that, although shore-protective works may have altered the spatial distribution of retreat rates, they had little effect on the overall rates of retreat. The absence of correlation between groin construction and retreat rates argues against the conventional wisdom at the time of their construction—that groins would produce wider beaches that would protect bluffs from wave attack. The ineffectiveness and even detrimental effects of groins on bluff stability have been documented more recently (Inman and Brush 1973, Larsen 1973, Mickelson *et al.* 1977). Existing data, however, are insufficient to evaluate the effects of the most recent shore-protective works that have been in place only for a few years.

Figure 9 shows that some individual bluff segments or small groups of bluff segments had very large retreat rates relative to adjacent segments. The regular shape of the shoreline at regional scale (Fig. 2) indicates that radical local differences in retreat rate do not persist over long periods of time. Data from Figure 9, however, indicate that local irregularities in the shoreline should have dimensions of 50-100 m. Bluffline irregularities shown in Figure 10 have such dimensions and thus are consistent with the recession data in Figure 9.

Of the factors examined, only variation in the lithology of the upper part of the bluff correlates with local changes in retreat rate. Over the 115-yr period, retreat rates of lacustrine bluffs are much greater than those of till bluffs (Table 1). Retreat rates in all units except the Zion City moraine vary substantially between early and late intervals; rates in lacustrine bluffs decrease, and rates in the bluffs formed by the Highland Park moraine increase. However, the minor changes in the regional retreat rates between the two time periods (particularly for the high bluff) and the fairly linear, regular shape of the southern Lake Michigan shoreline both indicate that spatial and temporal changes in retreat rates balance out over time periods of several decades to centuries and that a uniform regional rate of retreat prevails. For the last 115 yr, that retreat rate is about 20-25 cm/yr, a significant amount both in human and geological terms. Although bluff segments composed of materials more susceptible to surface erosion and landsliding than adjacent segments will experience anomalously high rates of retreat for limited periods of time, the data indicate that rates in such areas will eventually decrease and allow adjacent segments to "catch up." Although the mechanism by which this occurs is uncertain, we surmise that the long-term regional bluff retreat rate is controlled by the rate of erosion and retreat of the shoreface (extending from the beach at the base of the bluff to the lake bed offshore) rather than by lithologic variations in the upper part of the bluff. Throughout the area, the base of the bluff, the beach platform, and the shoreface all consist of hard clay till, covered in places by a thin veneer of sand and gravel (Foster and Folger, this volume). We can reasonably infer that a shoreface having essentially uniform lithology and physical properties and exposed to fairly uniform wave energy erodes and retreats at a uniform rate throughout the area. Local episodes of rapid bluff recession temporarily widen the beach platform and thus increase the distance from the base of the bluff to the shoreface, which does not necessarily react by eroding more quickly. In such areas, waves break farther from the bluff base, and wave energy will be dissipated before reaching the base of the bluff. This effectively retards bluff recession until the shoreface retreats closer to the bluff. Thus, the uniform lithology and erosion rate of the shoreface could effectively damp excessive bluff retreat in any one location and therefore constrain the geometry of the shoreline to its fairly linear form.

For the most recent period of observation, 1937-1987, retreat rates along the till bluffs are about the same as the long-term regional average. Retreat rates in the northern lacustrine bluffs are much greater than the regional average but are lower than those for the 1872-1937 interval; this decrease in retreat rate might be expected to continue if rate changes balance out through time. Rates for the southern lacustrine bluff are much lower for the late time interval as compared to the early time interval. Retreat rates there might be expected eventually to increase toward the regional average unless shore-protective works or widened beaches maintain the low rate.

The minute amount of sand contributed by bluff recession to the littoral system is consistent with recent surveys (e.g., Foster and Folger, this volume; Shabica *et al.* 1991) of nearshore sand volumes, which indicate that only thin, patchy sand bodies of small total volume are present along the Illinois shoreline. The predominantly fine-grained texture of the bluff materials thus has created a supply-limited littoral transport system.

What are the human consequences of the 20-25 cm/yr bluff recession rates in this area? Development in most of the area consists of medium-density single-family housing (large homes on fairly large lots) ranging in age from new to nearly 100 yr old. Setbacks from the bluff vary from almost zero to a few tens of meters. If the regional retreat rate prevailed everywhere (which it does not), then a house would need a 20-25 m setback from the bluff to survive 100 yr. Few houses have such large setbacks. Even though regional retreat rates are fairly constant, Figure 9 shows that retreat rates vary substantially from place to place for a given 50-100 yr period. The retreat that a specific part of the bluff might experience in any 50-100 yr period probably depends on several factors at that site and at nearby parts of the bluff: (1) the type and quality of shore protection, (2) the rate of retreat in the previous 50-100 yr period, (3) the local lithology and geotechnical properties of the bluff material, (4) the width of the fronting beach, and (5) the geometry of the shoreface in front of the bluff. Therefore, the data and conclusions from this study are relevant for regional planning rather than for site-specific engineering. Any planning for construction near the bluffs, however, must anticipate some amount of bluff recession and stipulate sufficient setback to insure the integrity of structure for its anticipated life.

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