TP 79-4

Changes in Rates of Shore Retreat, Lake Michigan, 1967-76

by

Edward B. Hands

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Shorelines tend to retreat landward as water levels rise. Less than 20 percent of the shore, lost as Lake Michigan rose between 1967 and 1976, was due to direct inundation; the remaining 80 percent was due to increased erosion in response to the higher lake levels. A simple correlation of lake level change and simultaneous shore retreat ignores the inevitable lag between process and response, but still accounts for 50 percent of the variance in shore retreat. A graphic summary of field data is presented to estimate effects of future lake level changes in similar coastal environments. Qualitative guidance is provided on how and when these estimates should be adjusted to reflect differences in environmental settings. Complete adjustment of the shore will be underestimated by the empirical relationship; but where lake levels change constantly, there will be many such instances of incomplete shore response.

PREFACE

This report is published to provide coastal engineers with information on rates of shoreline recession and on changes in these rates during the most recent episode of high water levels on the Great Lakes. This interim report is part of a study to develop and evaluate a profile response model to explain the effects of rising water levels on shore erosion. The work was carried out under the sediment hydraulic interaction program of the U.S. Army Coastal Engineering Research Center (CERC).

This report was prepared by Edward B. Hands, under the general supervision of Dr. C.H. Everts, Chief, Engineering Geology Branch, Engineering Development Division, CERC.

Assistance of the following individuals and organizations is gratefully acknowledged: the staff at Mears State Park who were extremely helpful during various data collection periods; P. Wood who assisted in the recovery of survey markers and generously provided transportation in the Silver Lake Dune area; the Tide and Water Level Branch, National Oceanic and Atmospheric Administration (NOAA), Rockville, Maryland, for providing lake level data; the Permit Branch, U.S. Army Engineer District, Detroit (NCE), for help in procuring aerial photography; the field office in Grand Haven, Michigan, for surveying bench marks in 1976; the 30th Engineering Battalion, Fort Belvoir, Virginia, for the 1976 profile survey; the National Ocean Survey (NOS), NOAA, for 1971 and 1975 profile surveys; and the Great Lakes Environmental Research Laboratory, NOAA (formerly the U.S. Lake Survey) for initiating shore-normal profiling in 1967 and 1969 at most of the sites used in this study.

The author appreciates the manuscript review and the helpful comments by Dr. C.H. Everts, Dr. C.H. Carter, and the U.S. Army Engineer Division, North Central.

Comments on this publication are invited.

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Ted E. Bishop

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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FIGURES

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

---

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

CHANGES IN RATES OF SHORE RETREAT,
LAKE MICHIGAN, 1967-76

by
Edward B. Hands

I. INTRODUCTION

1. Purpose.

Since 1967 the Coastal Engineering Research Center (CERC) has monitored beach profile development associated with a recent episode of sustained rising water levels on the Great Lakes. Ten profile stations were initially surveyed in 1967 by the U.S. Lake Survey (now a part of the National Oceanic and Atmospheric Administration-NOAA) for a littoral transport investigation at Pentwater Harbor, Michigan. Subsequently, the number of stations was expanded to encompass a 55-kilometer stretch of shore between Summit and Meinert Parks on the eastern shore of Lake Michigan (Fig. 1); 34 stations were surveyed by CERC at various 1-week to 4-year intervals between 1967 and 1976 to determine the nature of the long-term beach changes. This period of data collection overlaps a period of above-average precipitation in the Great Lakes Basin when the mean annual elevation of Lake Michigan rose 0.8 meter between 1967 and 1973. This report presents a summary of the changes in rates of shore retreat associated with this long-term increase in lake levels.

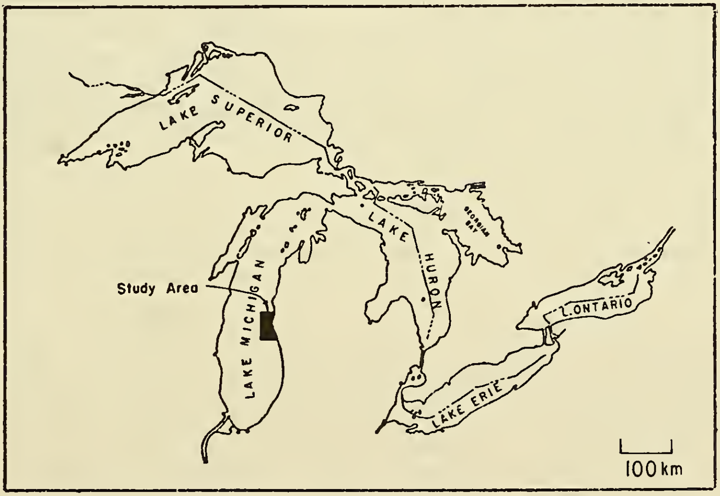

Figure 1. Location of study area.

2. Background.

Alternating periods of sustained rise and fall are characteristic of the annual mean surface elevations on the Great Lakes (Fig. 2). The cumulative effect of these persistent changes in lake levels frequently shifts monthly and annual mean surface elevations as much as a meter in a few years (Table 1).

Table 1. Major increases in annual mean lake level.

Lake	1925-29 (m)	1925-29 (ft)	1949-52 (m)	1949-52 (ft)	1964-73 (m)	1964-73 (ft)
Ontario	0.70	2.3	0.63	2.1	0.91	3.0
Erie	0.71	2.3	0.55	1.8	1.14	3.8
Michigan-Huron	0.99	3.3	0.88	2.9	1.45	4.8
Superior	0.47	1.6	0.19	0.6	0.26	0.9

Although the changes in water level on the Great Lakes (Table 1) may not appear large relative to tidal ranges at many ocean beaches, the long-term, gradual nature of the lake level fluctuations increases their effect on shore erosion and property loss. During years of low water, new property owners easily acquire a false sense of shore stability and, as a result, often build structures too near the shore. Storm erosion during years when the mean lake levels are high accelerates the rate of shore retreat, and causes considerable destruction to shore property on the Great Lakes. The long duration of high water periods also allows time for a relatively broad area of the nearshore zone to adjust to the elevated water surface (Hands, 1976). This adjustment involves offshore transport of large volumes of beach material and, as a consequence, greater shore retreat. After lake levels have declined sufficiently to reverse conditions, the waves transport some material from offshore back on the beach at most localities.

Rates of shore erosion fluctuate in response to the long-term hydrologic cycle. The impact of high lake levels, while relatively strong on all the lower lakes, is relatively weak on Lake Superior where the variations in water level are small (Fig. 2) and rocky shorelines are common.

No comprehensive survey of shore damage has been made on the U.S. side of the Great Lakes during the present episode of high water levels. The recent lake level rise is, however, similar to the previous rise which peaked in the early fifties (Fig. 2). A survey of economic loss sustained over a 12-month period coincident with the high levels of 1951-52 attributed $50 million worth of damage to wave erosion of U.S. property on the Great Lakes (U.S. Army Engineer Division, North Central, 1965). Considering inflation and recent shoreline development, it has been estimated that a recurrence of 1951-52 storms and high water levels would cause a minimum of $120 million damage (Great Lakes Basin Commission, 1976).

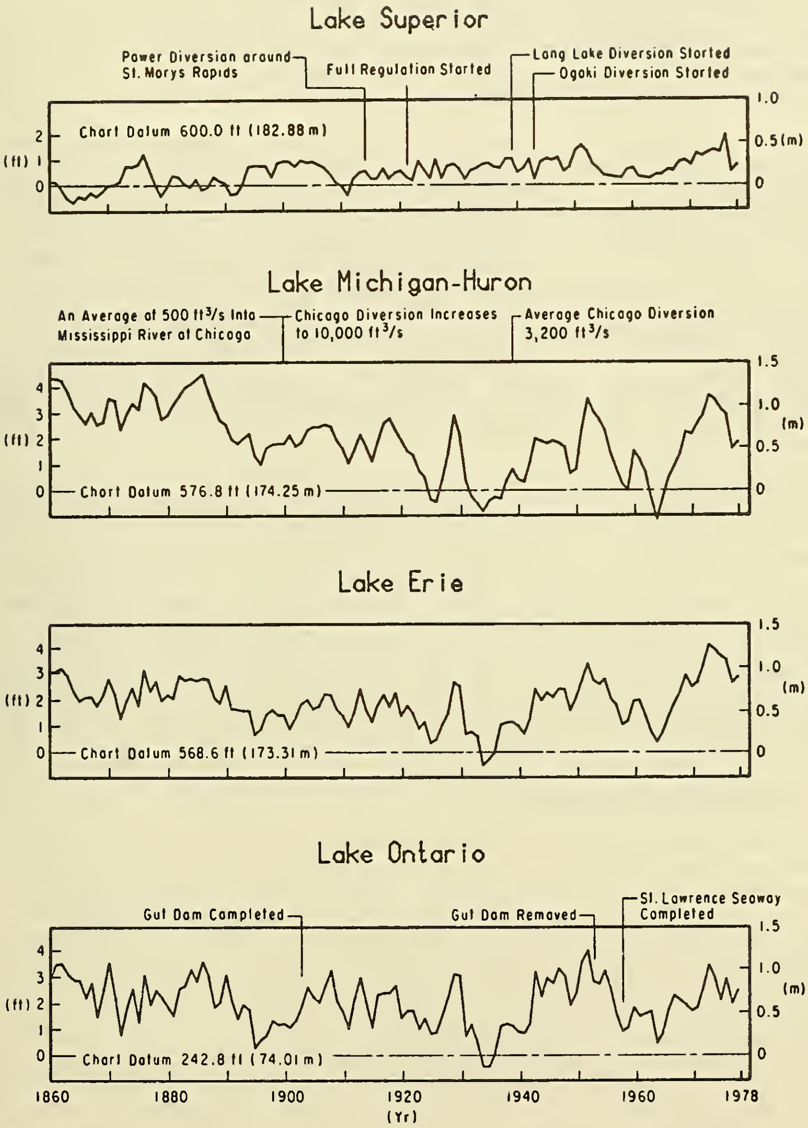

Figure 2. Historic changes in annual mean water levels on the Great Lakes, 1860 to 1978.

Recurrently, during periods of extreme shore damage, there has been public pressure to increase control over lake level fluctuations. A recent investigation considered the feasibility of regulating the entire Great Lakes system (International Great Lakes Levels Board, 1973). Although regulation of all five lakes is an engineering possibility, benefits were not found to be commensurate with costs.

Some control over lake levels already exists. Outflows from Lake Superior and from Lake Ontario have been controlled since 1921 and 1958, respectively (Fig. 2). However, regulation which reduces the range of levels on Lake Superior tends to increase fluctuations on Lakes Huron and Michigan. On the other hand, reduction of the range of levels on Lake Ontario can presently be accomplished without affecting the other lakes, because the major inflow is via Niagara Falls and the outflow is to the St. Lawrence Seaway via a series of control structures. Consequently, during the 1973-74 high water period, the outflow from Lake Ontario was increased 46 percent above its average flow to alleviate erosion and flooding problems. In spite of these improvements, both the water levels and the erosion problems remained significantly above their long-term average (Haras, 1975).

Because uncontrollable natural variations in water supply are so large, it is impractical to attempt to maintain a constant volume of water in any of the lakes. Regulation plans, nevertheless, continue to be reviewed to determine if modifications to currently controlled flows would reduce the total lake level-related damage to all concerns. Knowledge of how water level fluctuations affect erosion rates is important for determining how changes in regulation plans will affect riparian interests. Knowledge of fluctuations in lake level and their effect on rates of shore retreat is also important in the design of coastal construction projects, in recommending coastal setback, for planning proper beach-fill operations, and in evaluating the usefulness of short-term erosion measurements as a basis for extrapolating to longer periods on the lakes.

3. Previous Erosion Reports.

A number of previous studies related to shore erosion on the Great Lakes have been published by CERC. Shore changes were measured monthly from 1970 to 1974 at 17 sites widely scattered over Lake Michigan's eastern shore; results of the first 3 years of this study, reported by Davis, Fingleton, and Pritchett (1975) and Davis (1976) identify seasonal cycles in bluff retreat related to seasonal changes in lake level and storminess. Large, unexplainable spatial differences in bluff retreat were noted. It was hypothesized that these large differences might reflect the influence of offshore bathymetry on shoaling waves. Well-developed, multiple longshore bars dominate the eastern lake-shore bathymetry out to depths of about 6 meters (20 feet). Bars absorb part of the wave energy incident on the shore before it reaches the shore. The cross-sectional geometry, areal patterns, and textural composition of the longshore bars are described in Hands (1976). On the basis of surveys spanning a 4-year period, Hands also briefly discussed gradual changes in bar position, rates of shore retreat, and lake level change. A final CERC report (Hands, in preparation, 1979) will integrate bar migration, shore retreat, and lake level changes over the full period from 1967 to 1976; another final report will discuss the changes in shore retreat over the whole eastern shore between 1970 and 1974 (Birkemeier, in preparation, 1979).

Earlier CERC reports (Berg, 1965; Berg and Duane, 1968) cover long-term shore erosion and lake level changes and concern the behavior of beach fill at Presque Isle Peninsula on Lake Erie. Guidelines for monitoring the effect of shore protection works in the Great Lakes are presented in Coastal Engineering Research Center (1975).

Publications discussing wide aspects of Great Lakes shore erosion include State and Federal Government reports, journals, and student theses too numerous to review here. A compilation of published and unpublished data on erosion of the U.S. shoreline was prepared by Armstrong, Seibel, and Alexander (1976). An atlas by Haras and Tsui (1975) persents data on land use, historic flood and erosion damage, ownership, value, and physical characteristics for all the erodible Canadian shoreline of the Great Lakes. In 1976, the Canadian Government also initiated a 5-year program involving annual and poststorm surveys at approximately 160 stations on the Canadian shore of the Great Lakes.

II. FIELD METHODS

1. Study Area.

Profiles taken in 1969 near Pentwater Harbor on the eastern shore of Lake Michigan revealed little variation in beach profiles beyond alternate ridge-and-runnel development. However, when the 1969 profiles were compared with profiles taken during an evaluation of longshore transport made 2 years earlier, a significant landward shift of the whole active profile became evident. To evaluate the apparent long-term profile evolution, surveys have been repeated at the 10 stations originally established in 1967 within a kilometer of the Pentwater Harbor (Fig. 3) and also at 24 additional stations spread over adjacent 55 kilometers (Fig. 4).

2. Survey Periods.

Profiles are available for six different time periods: (a) summer of 1967, (b) spring of 1969, (c) fall of 1969, (d) spring of 1971, (e) fall of 1975, and (f) fall of 1976. Because the frequency of profiling and the extent of the study area changed progressively as previously collected data were analyzed, and the scale of changes was better understood, any given station may have been profiled up to four times during one of the survey periods. Over the years, as the shore continued to retreat, a series of *reference* monuments was established at most profile stations to provide local control if and when the *base* monument at that station was lost. The reference monuments were established above and landward of the original base monuments on the extended range azimuth for that particular

Figure 3. Profile stations in vicinity of Pentwater jetties.

Figure 4. Station location in the study area.

station. Table 2 gives the dates when each of the 34 stations were profiled, along with the daily mean lake level, and the distance of the shoreline from the base monument. Negative numbers in the table indicate that the shoreline had passed landward of the base monument by the given date.

3. Profile Procedures.

In 1967, the profiles were measured by a leveling cart. A leveling rod was attached to a four-wheel cart which was winched ashore. Every 5 meters the cart was halted and the elevation determined by an engineer's level located onshore. When the cart reached shore it was pulled by a Jeep down the beach to the next station and towed back offshore by boat. This method limited coverage to depths of less than 5 meters and required a moderately wide, unobstructed beach for efficient operations. In subsequent years, echo sounding was used to measure the outer part of the profile to a depth of 15 meters, but instrument leveling was still used to give overlapping coverage in shallow water and extend the profile to the dry beach. Since this report is concerned only with changes in shore erosion, no further discussion is made of the echo soundings or outer profiles. Instead, inner and outer profiles will be combined in a later report addressing the manner in which the entire active profile adjusted as lake levels rose (Hands, in preparation, 1979).

After 1967, the elevations on the inner profile were determined at the top and toe of the bluff (if one existed), the upper and lower limit of the swash zone, and at 5-meter intervals between the dune and the first longshore bar, using the engineer's automatic level. Horizontal control was by tag line, except in 1976 when distances were obtained from stadia intercepts using the "three-wire technique"--the procedure most commonly followed by military topographic surveyors. Reference monuments were tied to existing bench marks and second-order control stations surveyed by National Ocean Survey (NOS) in 1973. Additional vertical reference was obtained during profiling operations using a system of water level gages, water surface rod-readings, and a portable stilling well placed near the shoreline at each station. Profile accuracy in the horizontal is on the order of 1 meter from the base monument along the original azimuth. Vertical profile accuracy is about ± 5 centimeters.

III. TERMINOLOGY

Precise definitions are given that refine the meaning of several familiar terms used in this report. *Submergence* refers to the sinking of a coastal area relative to the mean water surface regardless of cause. Submergence can result from either subsidence of the shore or increases in the elevation of the water surface. *Emergence* refers to the opposite relative displacement, and when expressed numerically, both emergence and submergence refer to length measurements in the vertical. Coastal planners and property owners are often more interested in the resulting horizontal change in shoreline position: *shoreline retreat* is any landward migration of the shoreline; *advance* is the lakeward migration of the shoreline.

Table 2. Survey dates and shoreline positions.

Station	Date	Lake level (m)	Shoreline[1] (m)
1.0	27 Sept. 1976	176.72	-7.6
1.0	6 Aug. 1975	176.95	-16.7
1.0	8 May 1971	176.70	-1.7
1.0	28 May 1969	176.57	3.0
2.0	27 Sept. 1976	176.78	-3.0
2.0	26 Aug. 1975	176.92	-11.7
2.0	3 May 1971	176.61	13.0
2.0	15 May 1969	176.55	8.2
3.0	14 Sept. 1976	176.71	-24.3
3.0	11 Aug. 1975	176.91	-22.5
3.0	5 June 1971	176.80	-5.5
3.0	28 May 1969	176.57	-3.5
3.0	19 July 1967	176.33	7.5
3.5	25 Sept. 1976	176.71	-30.7
3.5	5 Aug. 1975	176.93	-32.0
3.5	21 July 1967	176.33	0.5
4.0	25 Sept. 1976	176.71	0.0
4.0	5 Aug. 1975	176.94	-19.5
4.0	5 May 1971	176.64	-5.0
4.0	21 May 1969	176.54	5.8
4.0	21 July 1967	176.33	11.7
4.5	25 Sept. 1976	176.71	15.5
4.5	5 Aug. 1975	176.94	4.5
4.5	21 July 1967	176.33	14.4
5.0	25 Sept. 1976	176.71	24.5
5.0	5 Aug. 1975	176.94	12.4
5.0	4 May 1971	176.66	11.2
5.0	21 May 1969	176.54	18.5
5.0	21 July 1967	176.33	20.5
6.0	12 Sept. 1976	176.77	5.1
6.0	13 Aug. 1975	176.93	-5.2
6.0	5 May 1971	176.68	-0.6
6.0	16 May 1969	176.53	8.6
6.0	27 July 1967	176.33	14.5
6.5	12 Sept. 1976	176.69	-5.4
6.5	13 Aug. 1975	176.95	3.0
6.5	22 July 1967	176.33	22.3
7.0	12 Sept. 1976	176.77	-9.0
7.0	13 Aug. 1975	176.92	-13.0
7.0	5 May 1971	176.67	3.8
7.0	16 May 1969	176.53	8.0
7.0	13 Aug. 1967	176.33	19.8
7.5	23 Sept. 1976	176.69	-8.5
7.5	15 Aug. 1975	176.93	-23.4
7.5	22 July 1967	176.33	9.0
8.0	11 Sept. 1976	176.77	-14.6
8.0	11 Aug. 1975	176.91	-23.7
8.0	6 May 1971	176.68	-6.1
8.0	21 May 1969	176.54	4.0
8.0	22 July 1967	176.33	4.0
9.0	12 Sept. 1976	176.77	4.8
9.0	13 Aug. 1975	176.92	-6.4
9.0	30 Apr. 1969	176.45	5.0
10.0	11 Sept. 1976	176.76	-1.2
10.0	13 Aug. 1975	176.93	-10.8
10.0	7 May 1971	176.64	3.5
10.0	26 Apr. 1969	176.44	9.5
11.0	13 Aug. 1975	176.94	-999.0
11.0	13 May 1969	176.56	-0.7
12.0	10 Sept. 1976	176.72	6.5
12.2	13 Aug. 1975	176.94	3.5
12.0	30 Apr. 1969	176.45	7.1
13.0	24 Sept. 1976	176.66	-9.0
13.0	13 Aug. 1975	176.94	-17.4
13.0	13 May 1971	176.62	-7.9
13.0	16 May 1969	176.53	3.3
14.0	24 Sept. 1976	176.66	-12.3
14.0	12 Aug. 1975	176.91	-13.6
14.0	30 Apr. 1969	176.45	18.3
15.0	24 Sept. 1976	176.66	37.5
15.0	12 Aug. 1975	176.91	25.4
16.0	24 Sept. 1976	176.66	-13.8
16.0	12 Aug. 1975	176.91	-15.8
16.0	30 Apr. 1969	176.45	20.0
17.0	10 Sept. 1976	176.73	13.6
17.0	13 Aug. 1975	176.93	4.6
17.0	7 May 1971	176.65	21.0
17.0	26 May 1969	176.57	10.0
19.0	23 Sept. 1976	176.70	-15.0
19.0	7 Aug. 1975	176.90	-27.5
19.0	10 May 1971	176.68	-7.0
19.0	19 Aug. 1969	176.53	-4.5
20.0	24 Sept. 1976	176.66	-1.7
20.0	13 Aug. 1975	176.94	-5.6
21.0	20 Sept. 1976	176.76	6.5
21.0	13 Aug. 1975	176.94	-0.2
23.0	20 Sept. 1976	176.76	5.3
23.0	12 Aug. 1975	176.92	5.5
23.0	7 June 1969	176.61	15.0
24.0	20 Sept. 1976	176.76	7.5
24.0	12 Aug. 1975	176.90	8.6
24.0	14 May 1971	176.68	10.0
24.0	7 June 1969	176.61	11.5
26.0	20 Sept. 1976	176.74	-1.6
26.0	12 Aug. 1975	176.92	-5.9
26.0	14 May 1971	176.67	5.2
26.0	9 May 1969	176.60	11.5
27.0	20 Sept. 1978	176.76	-19.8
27.0	12 Aug. 1975	176.92	-15.3
27.0	9 June 1969	176.60	9.5
28.0	20 Sept. 1976	176.72	16.5
28.0	12 Aug. 1975	176.92	21.4
29.0	20 Sept. 1976	176.76	22.3
29.0	12 Aug. 1975	176.82	19.8
29.0	14 May 1971	176.69	35.1
29.0	3 June 1969	176.60	42.0
32.0	25 Sept. 1976	176.71	57.5
32.0	11 Aug. 1975	176.92	50.2

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[1] Negative values indicate the shoreline was by that date landward of the base monument.

The *shoreline* is the intersection of the beach with the stillwater surface or, if specified, some other datum (e.g., 176.33-meter shoreline). The relative elevation of the stillwater level can change with time. Submergence causes the shoreline to retreat by direct *encroachment* of the water over the land. *Withdrawal* of the water during emergence advances the shoreline.

Total horizontal migration of the shoreline can be more or less than that caused by encroachment, depending on whether erosion or deposition prevails at the shoreline. The lateral migration of a *specified contour* is referred to as *progradation* if the contour moves toward the center of the basin, and as *recession* if the contour moves away from the basin. Shoreline retreat (Fig. 5) is thus an inclusive term referring to the total landward horizontal shift or the algebraic sum of encroachment (a function of submergence) plus recession (a function of erosion). Shoreline retreat implies that either local recession or encroachment has occurred, but is unspecific as to which (or both) is responsible for the landward shift in shoreline position.

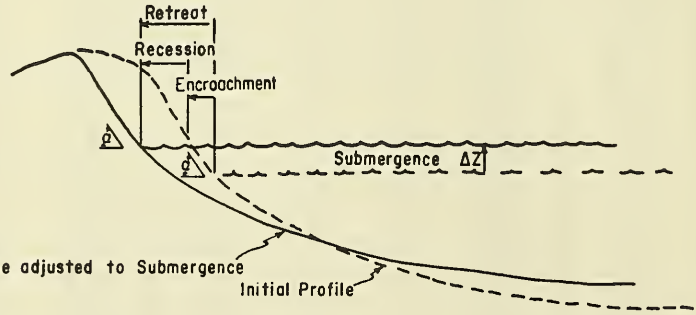


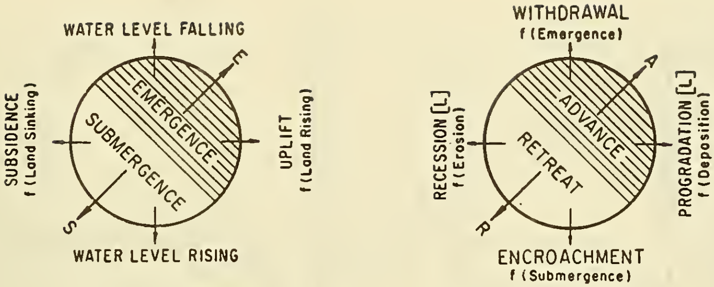
Figure 5. Terminology of retreat. Retreat = encroachment + recession
encroachment = $\Delta Z \cot \alpha$.

In geology, the terms *transgression* and *recession* have definitions closely related to those discussed above. In fact, these terms were used by Hands (1976) to mean exactly the same thing as encroachment and withdrawal. The reason for substituting encroachment and withdrawal in this study is to avoid using two terms that sound so similar (recession and regression) in reference to two opposite shoreline changes. The meaning and hierarchy of the terms used in this report are shown in Figure 6.

IV. DATA PRESENTATION

1. Shoreline Retreat.

Although a simple procedure is used for plotting all shore retreat and recession data in this report, the format is slightly different from the usual method. A short step-by-step explanation is given below to



a. Vertical Changes

b. Horizontal Changes

Figure 6. Terminology of vertical and horizontal shoreline changes.

accustom the reader to viewing the data from the slightly different perspective employed here.

The most direct way to represent retreat of the shoreline would be to superimpose a set of shoreline maps. However, to depict on a page even a small part of the present study area, distances normal to shore would have to be exaggerated; otherwise, even where the shoreline has retreated 35 meters, the change would not be evident. For example, note that in the aerial photo at the bottom of Figure 7, all shoreline positions for the last 10 years would overlie one another and be indistinguishable at this scale. Expanding the scale perpendicular to shore pulls the shorelines apart as shown above the photo. Note the expansion also greatly distorts shoreline shape. Since the primary interest is in shoreline retreat, not shape, all attempts to show shoreline shape could be abandoned and all shorelines referenced to their position on either the initial or the final survey. Because the year of initial surveying differs among stations, shoreline positions are referenced at the top of Figure 7 to their final positions (as determined in October 1976).

Figure 7 shows a two-step transformation of shoreline data (from map view), first to exaggerated distance from base line, then to exaggerated distances from the 1976 shoreline. Because the shoreline protrudes about 10 kilometers lakeward in the vicinity of Little Sable Point (Fig. 4), it is infeasible to depict both shoreline shape and changes in shore position for the entire study area on the same figure; therefore, in all the remaining plots the shoreline and contour positions are referenced to their final positions as determined in the 1976 survey at each station. The plots will also have the same exaggeration of scale perpendicular to shore as shown at the top of Figure 7.

Shore retreat throughout the study area is shown in Figure 8. Note that two different horizontal scales are used to permit comparison of the closely spaced measurements near Pentwater Harbor with measurements from the more widely spaced stations elsewhere. The straight lines connecting 1967, 1969, and 1975 data points are plotted to quickly identify

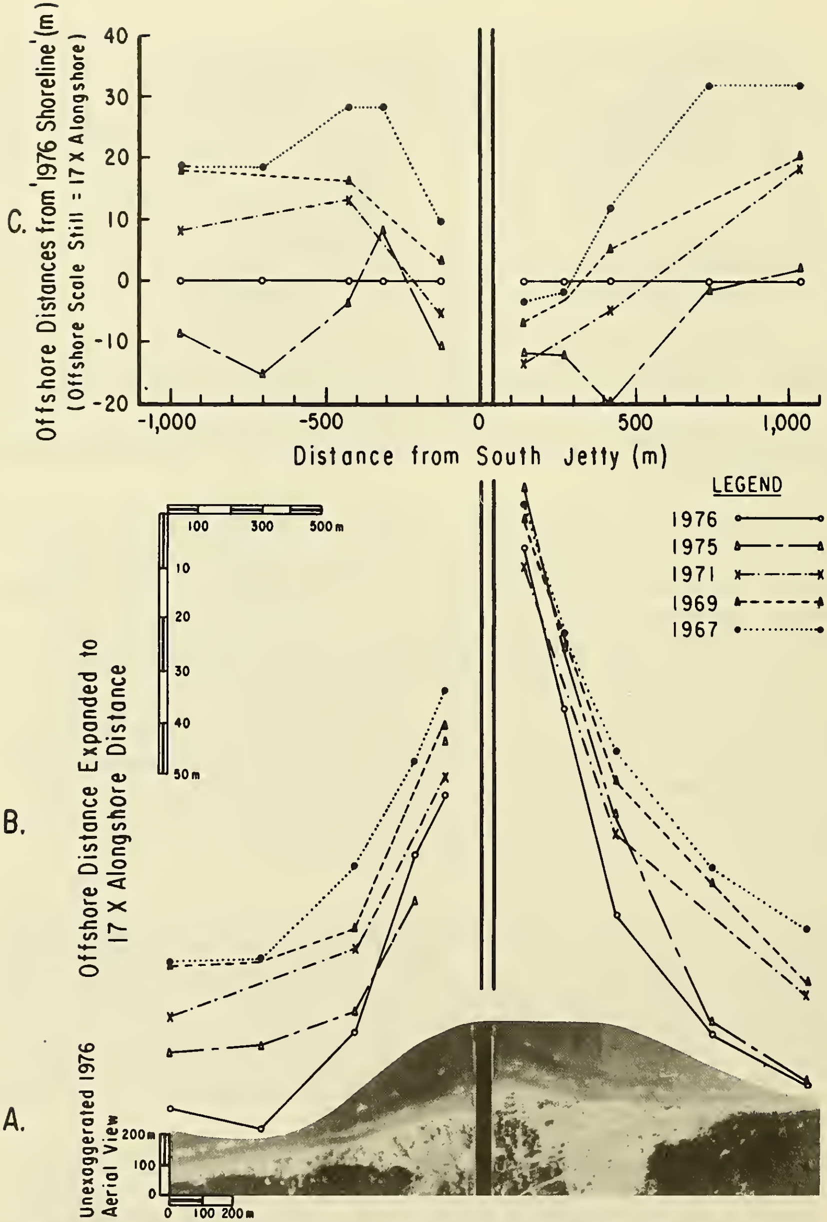


Figure 7. Different formats depicting changes in the shoreline adjacent to the Pentwater jetties. The top format (also used in Figures 8 and 9) was obtained from the unexaggerated aerial view by a two-step transformation (A to B, then B to C).

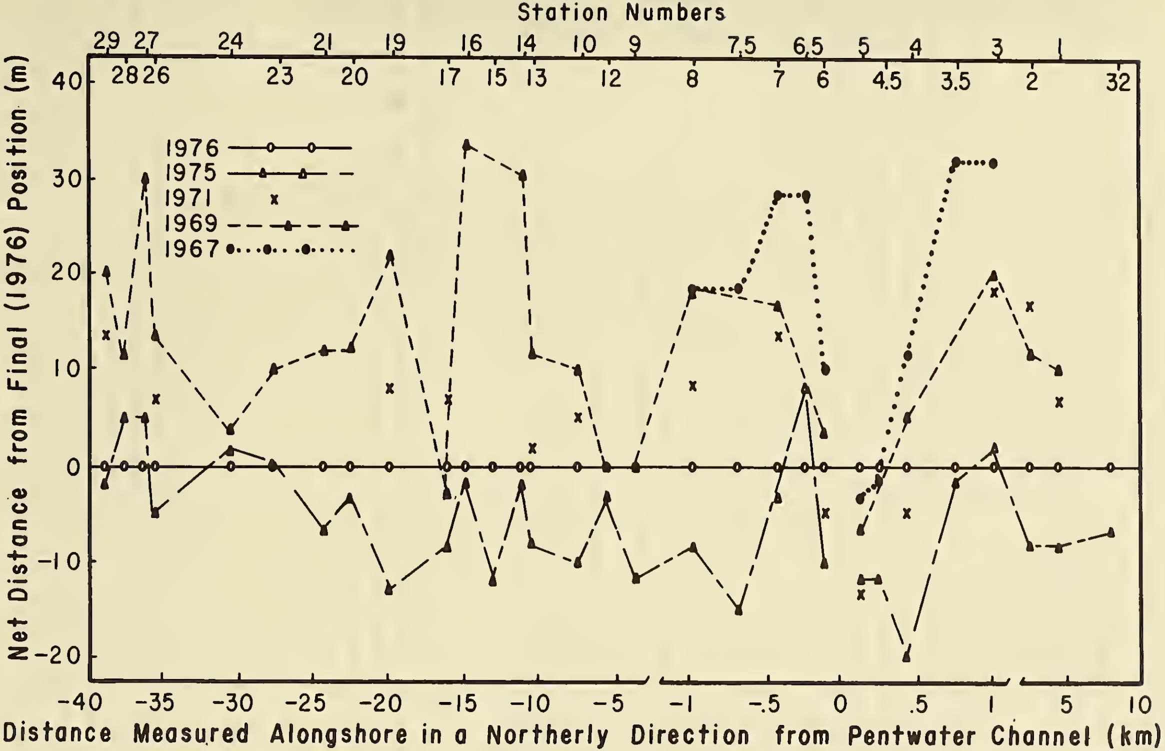


Figure 8. Change in shoreline position. Earlier shorelines are referenced to their final position measured in 1976; positive values mean the shoreline was lakeward of its final position. The 1976 shoreline is artificially straightened; true shoreline curvature is in Figure 4. Exact survey dates are given in Table 2.

measurements from common survey periods; the lines do not necessarily reflect actual shoreline position between measurement stations.

Large positive ordinate values in Figure 8 indicate points where the shore retreated a large distance. Extreme negative values indicate where the shoreline advanced a large distance lakeward. Where data points cluster closely, the shore remained relatively stable.

The net retreat of the shoreline between 1969 and 1975 averaged 18 meters or 2.9 meters per year, but as Figure 8 shows, longshore variability in retreat was extreme, ranging from 0.3 to 5.7 meters per year. Because of the large variation observed between adjacent stations, knowledge of the 6-year retreat at a single point by itself would be of little help in estimating the rate of retreat at another point a kilometer away. This is not to disparage the calculation of an average rate based on several measurements up and down a particular stretch of shore. Confidence in such an estimate of the mean can be increased without limit by increasing the number of measurements. The uniformly small rates measured at four stations adjacent to the Pentwater jetties indicate that particular stretch of shore suffered less retreat than did the surrounding 50 kilometers. In fact, the shore experienced a net advance at two stations in Mears State Park just north of the jetties and nowhere else except at station 17, on the tip of Little Sable Point (see Fig. 4).

The shoreline remained remarkably stable at stations 24 and 12. At station 9 (about 2 kilometers in a northerly direction from station 12), there was negligible net retreat, but this resulted from early retreat being compensated by progradation sometime during the last 13 months of study.

Falling lake levels and progradation during the last year of the study advanced the shore at 24 of 30 stations. Though the additional beach width gained during this last year was considerable, only three stations (4.5 and 5, just north of the jetties, and 17 on the tip of Little Sable Point) advanced enough to regain their 1969 shoreline. The average gain (each station given equal weight) between 1975 and 1976 was 4.3 meters or about 20 percent of the retreat which had occurred during the previous 6 years.

2. Recession.

The effect of declining water levels and of sediment deposition was discussed previously as both contributing to the advance of the shore and the partial recovery of former beach widths during the last 13 months of study. However, the relative importance of the two distinct processes was not identified. Progradation refers to displacement of a certain topographic contour toward the lake; recession refers to displacement of that contour toward the land. The exact magnitude of recession at the specified datum will depend on the elevation of the datum specified as well as the position along the shore where the measurement is made.

Even in the usual simplified model (Fig. 5) the magnitude of recession depends on the elevation where the recession is measured. Shore recession by definition is measured at the elevation of the final water level, between the points where the final water level intersects the initial and the final profiles. In the model, recession also occurs at all other elevations where the initial bottom sloped at a greater angle than the *effective angle of profile adjustment;* i.e., where the slope was greater than the ratio of vertical to horizontal displacement of the idealized profile (Fig. 5). At those elevations where the bottom sloped at an angle less than this effective angle, the contours would move lakeward, even as the whole profile and features on it move up and landward. In nature, shore profiles are not smooth and do not always increase in depth lakeward. Thus, progradation may occur at several elevations, while recession (net erosion) occurs elsewhere and the overall profile migrates landward. The profile shape can also change as the shore recedes. The degrees to which these natural complications increase the variability in measurements of contour migration is shown in Figure 9.

In the first plot at the top of Figure 9, the progressive recession of the 176.92-meter contour (at the average elevation of the lake surface during the 1975 survey) can be read on the vertical axis. Between 1969 and 1976, the average net recession at 176.92 meters was 10.5 meters and the maximum net recession was 28 meters at station 14. Progradation occurred at stations 4.5, 5, and 17. The 176.92-meter recession is very similar to that of total shore retreat (see Fig. 8). The total shore retreat is, of course, a little larger (averaging 12 meters and with a maximum of 34 meters) because it includes transgression resulting from 0.2 meter of submergence. The areal patterns of recession and retreat are, however, virtually identical. At slightly lower elevations (shown in succeeding plots in Fig. 9) the overall pattern of recession remains much the same, though the magnitudes of recession progressively depart from the magnitudes of shore retreat. This simply means that the overall pattern of shore retreat, which could theoretically have been obtained from aerial photos, reflects the overall pattern of actual recession of the upper beach face, which could not be obtained without repeated ground surveys.

If progressively lower elevations are observed in Figure 9, the similarity between recession and retreat deteriorates rapidly. Recession at an elevation of 176.33 meters (the level of the lake surface during the 1967 survey) is shown at the top of the second column of plots in the figure. The spread of recession values encountered at the different stations has increased, but the same overall pattern remains recognizable: zones of maximal net recession occurred at the south end of the study area, around Little Sable Point and at two points a few kilometers north and south of the harbor. At still lower elevations, the increased longshore variability overwhelms similarities between recession and shoreline retreat. Not only would the magnitude of recession change drastically if measured at slightly different elevations on the lower beach face, but even the longshore pattern (i.e., the area of most and least severe erosion) would be obscured in measurements made only at these lower

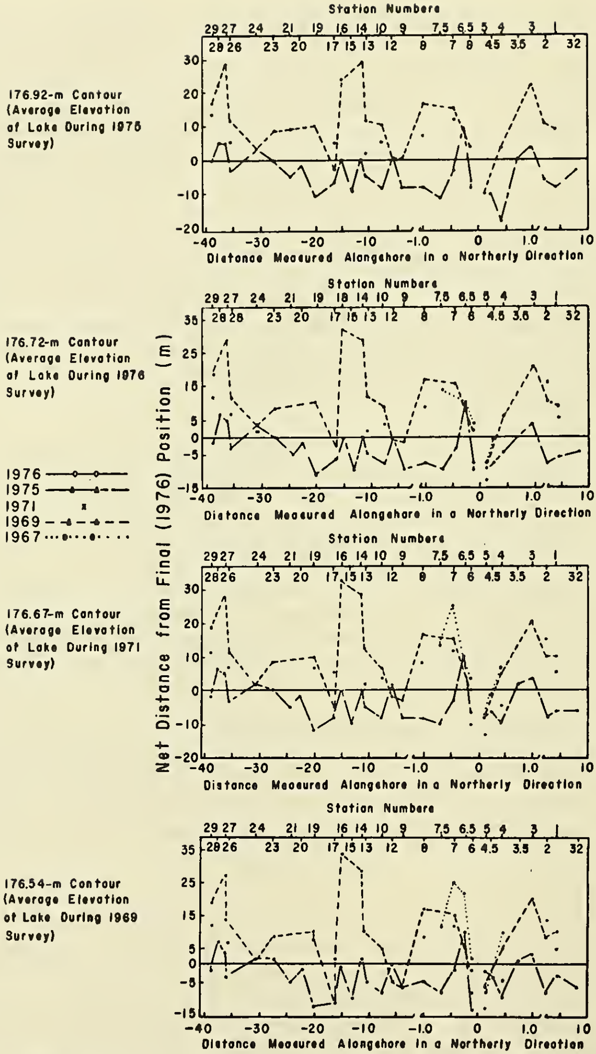


Figure 9. Time changes in positions of various contours intersecting the beach face. Distance of selected contours from their final position was determined in the October 1976 survey. Positive ordinate values indicate net recession between the indicated year and the final (1976) survey; negative values indicate net progradation for the indicated period.

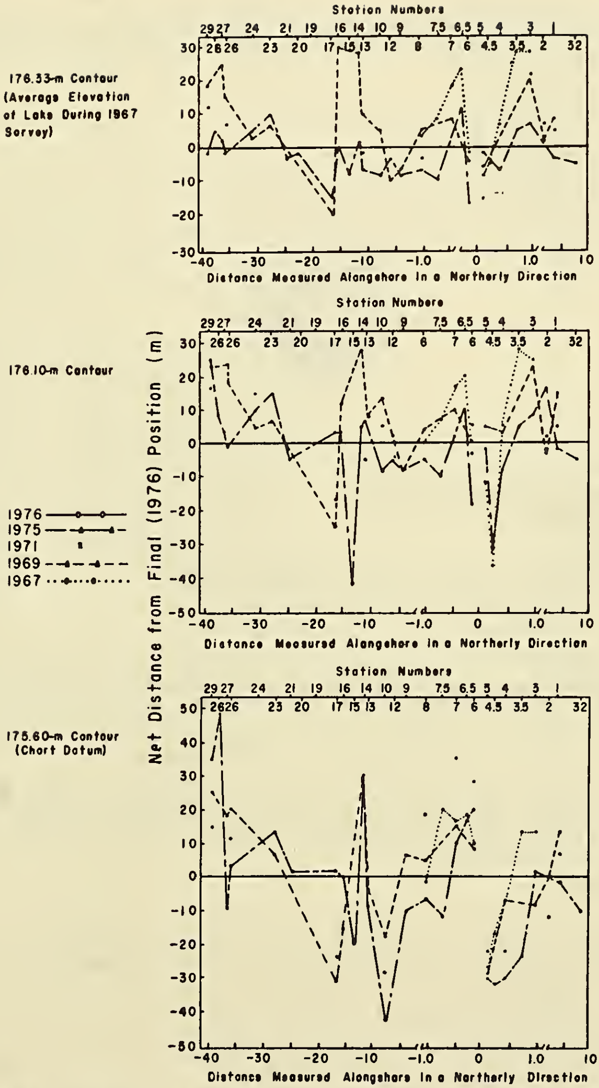


Figure 9. Time changes in positions of various contours intersecting the beach face. Distance of selected contours from their final position was determined in the October 1976 survey. Positive ordinate values indicate net recession between the indicated year and the final (1976) survey; negative values indicate net progradation for the indicated period.--Continued.

elevations. All the foregoing reference contours fall on the beach face; i.e., intersect the profile between the berm and the first longshore trough (Fig. 10).

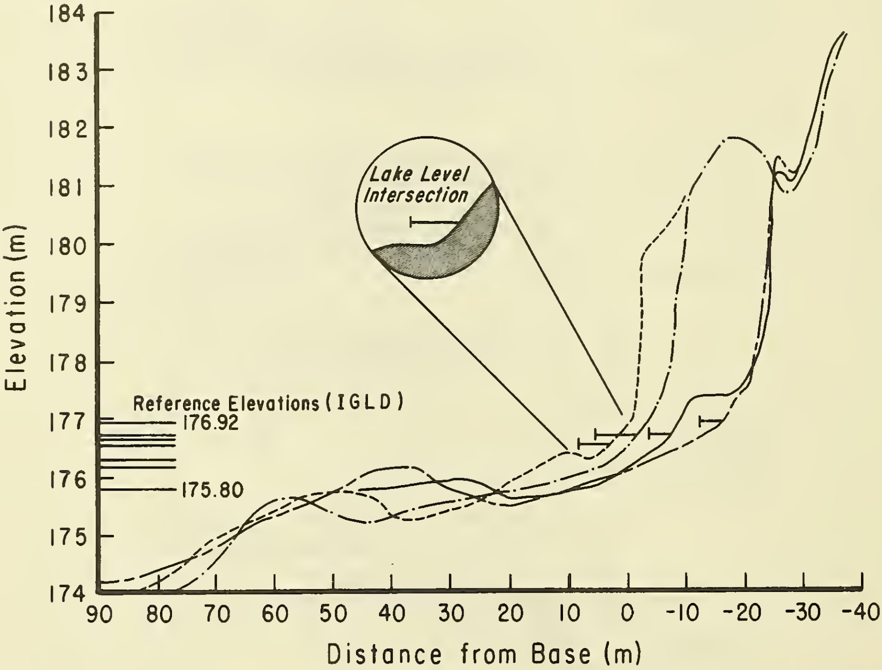


Figure 10. A fairly typical inner profile. Note the various reference elevations (International Great Lakes Datum - IGLD) at which contour migration was measured to determine rates of beach face recession plotted in Figure 9.

3. Encroachment.

Encroachment refers to the loss in shore width due directly to submergence. Given only the initial profile, the encroachment which would result from a subsidence of Δz is exactly $\Delta z \times \cot \alpha$ (where α is the slope of the profile between initial and final mean water elevations). This simple calculation may be sufficient to indicate the extent of potential flooding problems along low-lying coasts. The same approach has also been used in the scientific literature to estimate long-term effects of sea level rise, but this is a severe oversimplification because encroachment by the sea is only one aspect of shore retreat. Submergence will usually increase erosion rates causing extensive shore recession which contributes to further shore retreat. Between 1969 and 1975, a period of persistent submergence on Lake Michigan, the overall retreat of the shore exceeded the encroachment by a factor of 5 (the total retreat averaged from all stations was 17.9 meters, of which only 3.4 meters was due to encroachment). Furthermore, the amount of encroachment at a given station, while predictable, would have given no clue to the final amount of shore recession (Fig. 11).

The amount of recession depends on the exposure and resistance of the beach to erosive forces. Within the range of conditions observed on the lake, the flatter foreshores showed no tendency to recede more or less than steeper foreshores. Moreover, shore recession continued in some cases even after the water levels began to decline. Hence encroachment, depending only on steepness of the foreshore and the change of water levels, is a poor measure of total shore retreat.

V. DATA INTERPRETATION

1. Spatial Variation in Retreat Rates.

The average rate of shore retreat for the whole study area was 2.9 meters per year (1969 to 1975), but there were wide variations (see Fig. 8). The maximum rate of retreat (4.6 meters per year) was observed at station 16; progradation caused the shoreline to advance at three stations (maximum of 6 meters at station 5). Two of the stations where the shoreline advanced lakeward are in Mears State Park, just north of the Pentwater jetties. The park personnel employ a number of shore protection measures at this locality. Each fall a series of snow fences is installed in multiple rows along the shore to catch and hold windblown sand during the winter. Each spring the fences are removed, the beaches are graded, and the sand that had blown inland and accumulated in the camping area and parking lots is scrapped up and added to the beach opposite the swimming area. Since 1973 park personnel have also been nourishing the beach with a small part of the 50 to 70X10^3 cubic yards which is dredged annually by the U.S. Army Corps of Engineers from the Pentwater Channel. In each of the years 1973, 1974, and 1975, about 5,000 cubic yards of the sand removed from the channel by bucket dredge was dropped across the north jetty onto park property. The park staff widened the beach in the bathing area using the dredged sand together with about an equal amount of sand removed from inland dunes, (G. Zeine, Mears State Park Supervisor, personal communication, 1977). In 1976 the channel was deepened with a hydraulic dredge, and about 7,000 cubic yards was pumped onto the beach between the north jetty and station 4.5. In addition to these steps, three rockfilled gabion groins were installed near station 4.5 in 1973 as part of the Michigan Demonstration Erosion Control Program (Brater, et al., 1977). Concern for swimmers' safety led to replacement of the outer ends of the wire gabions with sandbags the next spring.

The effects of these various shore protection efforts at Mears State Park, together with the protection the jetties afford by blocking some of the beach from southern exposure and acting as a terminal groin for the fill, are judged responsible for causing the shore to prograde lakeward at stations 4.5 and 5 while for the same 7-year period the adjacent

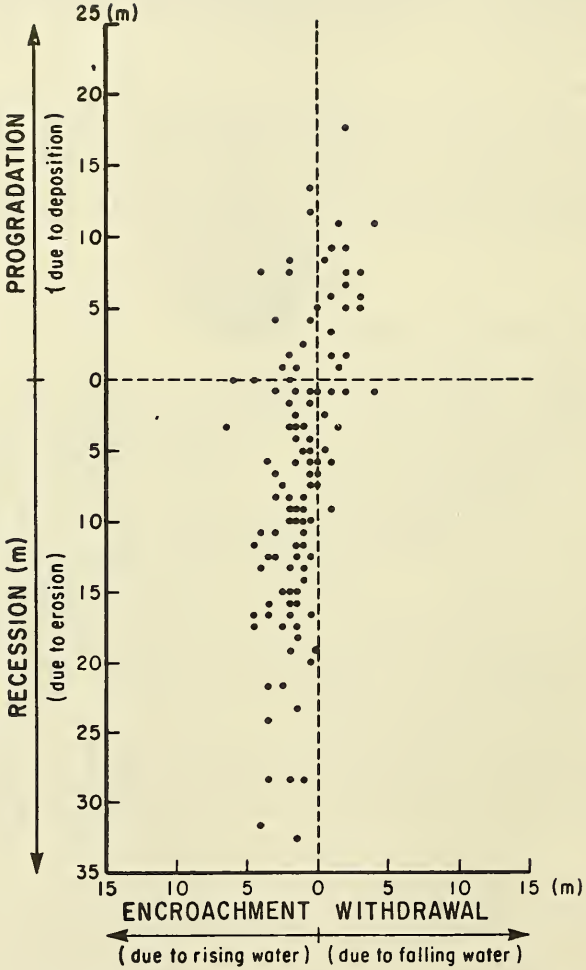


Figure 11. Encroachment versus recession as a cause of shoreline retreat. The total retreat of the shore is the sum of encroachment by the higher waters plus recession of the beach. Given only the initial profile shape, the encroachment that would result from different water level changes can be predicted exactly. Recession would be more difficult to predict, and though sometimes neglected, recession was by far the more significant of the two components contributing to retreat on the sandy lake shore.

beaches retreated an average of 14 meters.

No adequate explanation can be given at present for the other instance of a net lakeward advance of the shoreline at station 17, located on the tip of Little Sable Point. The shore opposite station 17 alternately prograded, receded, and then prograded between the 1969, 1971, 1975, and 1976 surveys. On the final survey, the shoreline was 3.6 meters lakeward of its initial position, but it had fluctuated through a range of 16.3 meters. Photos taken at the time of the 1975 and 1976 surveys at station 17 (Fig. 12) suggest that as a result of the longshore passage of a sand wave (i.e., a lakeward protrusion of the shoreline, sometimes referred to as shore rhythm, crescentric planform, beach pod, etc.), the shore can alternately prograde and recede over such distances. Additional shoreline protrusions occurred where bars merged, at their updrift ends, with the beach face (Fig. 13). Smaller shoreline undulations marked the location where the inner bar frequently forms a cellular pattern in plan view. Shoreline undulations seem slightly more prominent on Little Sable Point than elsewhere throughout the study area; however, this is not a complete explanation for the shoreline behavior at this locality. While station 17 showed net progradation, stations 14, 16, and 19 on Little Sable Point were among the most rapidly retreating during the study period. Shore retreat would probably have been extensive at station 18, had the property owners not rebuilt and maintained an earlier (1950-51) timber bulkhead to protect a cottage near the edge of the high bluff which backs this site. Likewise, terrace erosion reported by Davis (1976) for a point between stations 16 and 17 (D6 in Fig. 4) was among the highest he determined in a 1970 to 1973 study of 17 sites spread over almost the entire length of the eastern shore of Lake Michigan. Other measurements in the vicinity of the point also showed rapid retreat during recent years. It is not known why Little Sable Point during the last several thousand years has been the site of massive sand dune accumulation (apparently fed by a convergence of littoral transport from both the north and south) should now be the site of the most rapid shore retreat. It is equally difficult to explain why a shorter section of shore on Little Sable Point (represented by station 17) alternately prograded and receded, producing only a small net change in the midst of this presently rapidly receding section of shore.

2. Temporal Variations in Average Retreat Rates.

Engineers are sometimes criticized for placing too much reliability in average retreat rates derived from a limited number of measurements widely spaced along the shore. If the dynamics of beach cusps, rip cells, or the possible effects of edge waves were of interest, then obviously the temporal and spatial scales of these processes would have to be considered in planning the response measurements. More often, however, the practicing engineer is interested in overall conditions affecting a large section of shore, and in long-term results affecting the lifetime of a project or structure (e.g., 30 years). It is worth pointing out that as the temporal scale increases some of the problems that originally contaminated data tend to cancel one another rather than accumulate as the

Figure 12. A shoreline indentation opposite the Little Sable Point light in August 1975 introduces variability in shore retreat as it migrates alongshore.

Figure 13. Views of shoreline undulations which sometimes form where the inner bar merges with the shore.

time between observations is extended.

A problem frequently faced by engineers is to choose a sampling interval adequate to determine a mean recession rate for a given beach. The precision of the estimated mean recession will depend on the inherent longshore variability of recession which can be large (see Fig. 11); e.g., 4 meters of advance and 34 meters of retreat were measured over the same 7.4-year period at two stations less than 2 kilometers apart. It is well known that for a fixed level of longshore variability, the precision of the estimated regional mean can be improved by increasing the number of survey stations. Less well recognized is that inherent variability usually does not increase greatly with time. Thus, the probable error of mean *rates* and the *percent error* in mean recession tend to decrease with time. The variance of these estimates would also tend to decrease (thus, the precision increase) in direct proportion to the number of years between surveys.

The claim that longshore variability in recession does not increase with time nearly so fast as does recession itself, is supported by observing the spread among individual recession measurements from a fixed set of stations over 2-, 4-, and 6-year intervals (1969-71; 1971-75; 1969-75). While the mean recession grew from 5 to 12 to 17 meters, the standard deviations of the measurements only increased from 6.2 to 7.1 to 7.6 meters. Nearly constant variability may be partially related to sand-wave migration, etc., which tends with time to merely distribute the same variability uniformly along the shore.

The clear improvement with time in the precision of the estimated mean rate is shown by the histograms of retreat rate measurements in Figure 14. Note at the top of the figure that the variability in retreat rates based on net change over a 5-month period is relatively large. An estimate of the true rate of recession would require a relatively large number of measurements, even if the need is only to typify the mean recession for this short period. As the length of time between observations increases, the individual measurements more closely cluster about their mean, and thus an estimate from a fixed number of measurements tends to better represent the true mean rate for that section of beach.

Variability need not always decrease with time, nor with number of observations, if the character of the processes themselves changes. This is where the engineer's judgment must be applied in selecting appropriate historic data to fit the specific case at hand. Various aspects of how lake level changes affect the process of shore erosion are discussed later in this report.

3. Effects of the Recent Lake Levels on Shore Retreat Rates.

The annual cycle of high lake levels in summer and low lake levels in winter was superimposed on a fairly steady rise in mean level that began several years before the first profiles were taken and ended at a record high annual mean elevation for this century in 1973 (see Fig. 15). The

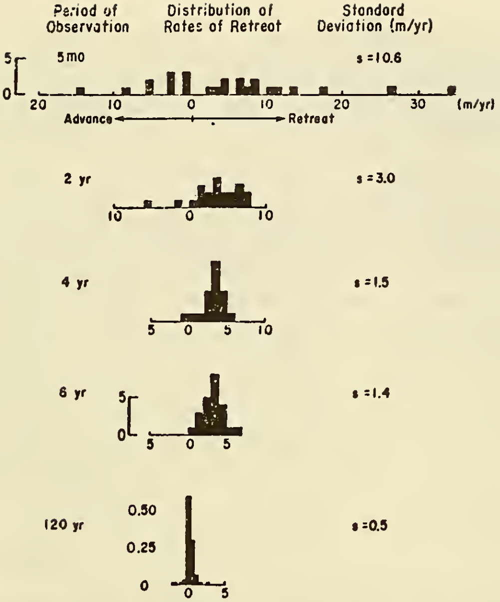


Figure 14. Distributions of measured retreat rates. Note the spread in the rates of shoreline change decrease as the period of observation lengthens. The histogram of 120-year rates is not strictly comparable to the others as it is based on a larger number of observations and includes effects of variations encountered around the entire perimeter of the lake (Powers, 1958); however, it still illustrates a continued reduction in the spread of retreat rates as the time interval lengthens.

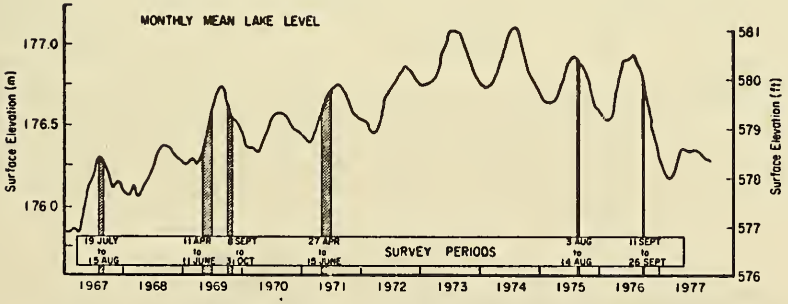


Figure 15. Lake Michigan hydrograph showing changes in lake level between survey periods.

mean lake level remained essentially stable in 1974 (i.e., repeated the sequence of record high monthly means set in 1973), then began dropping slowly in 1975. During the last half of 1976, precipitation in Lakes Superior and Michigan basins was down 40 and 45 percent, respectively, from their long-term averages, and Lake Michigan levels began to fall rapidly.

The relationship between shore retreat and lake level changes is indicated in Figure 16. The ordinate value of each point is the difference between the daily mean lake levels from one survey to the next, several years later; the abscissa is the distance the shore retreated between surveys. The general tendency of shore retreat to be proportional to the change in water level and the deviation of individual measurements from this trend are evident.

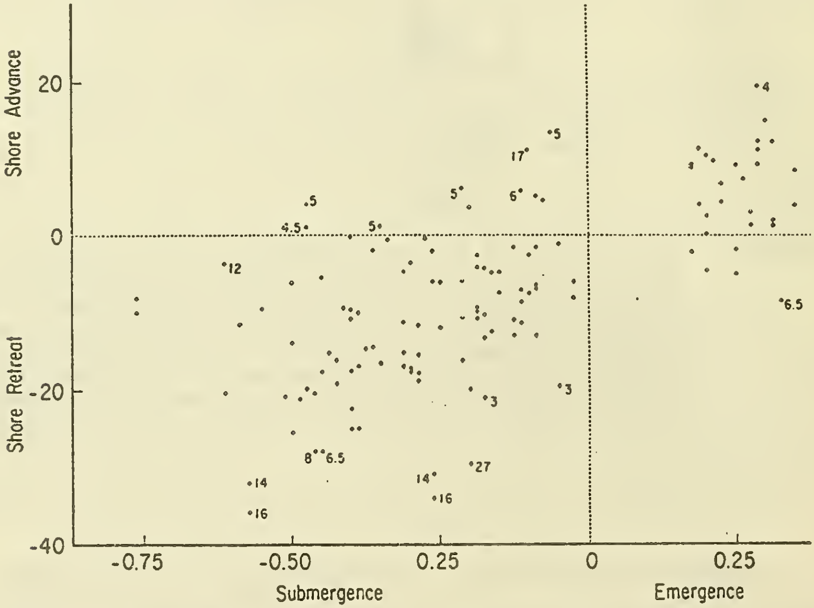


Figure 16. Submergence (the rise in water level) versus retreat (the landward migration of the shoreline). Data on emergence were obtained between 1975 and 1976, several years after the lake levels began to decline slowly. Outliers far from the evident linear trend are identified by station number.

As expected, local variations in wave exposure, in the nature and orientation of the shore, in offshore topography, etc., cause the individual measurements to scatter widely about the mean predicted solely on the basis of the lake level change. Those retreat values that deviate most from the linear relationship are identified by station number. These stations are mostly located either in the immediate vicinity of the Pentwater jetties or on Little Sable Point--areas of anomolous recession as already pointed out in the discussion of spatial variations in retreat. The points to the right of the vertical axis in Figure 16 all represent changes during the last year of study and just before the rapid fall in lake levels. Note that the shoreline at most stations shows an advance for the first time during the period 1975 to 1976. Apparently the recent cycle of accelerated shore retreat was complete, or nearly so, given the lower water levels in 1976.

Because water levels are rarely stable for long periods of time, almost any increase or decrease in erosion measured on the Great Lakes may be partially attributable to a difference in water levels. In many instances, the data shown in Figure 16 could serve as a basis for estimating how much of the recession could have been caused by water level changes and how much must be due to other causes. Examples of this application are given in Appendix A.

4. The Timelag Between Lake Level Perturbation and the Reestablishment of Profile Equilibrium.

A tentative model describing the general response of the shore to rising lake levels was proposed by Hands (1976). Based on what appeared to be a more rapid adjustment of the offshore bathymetry, and an oversteepening of the upper profile in surveys through 1971, Hands suggested that the lakeshore would continue to recede about another 11 meters before regaining equilibrium, even if the lake level stabilized at the 1971 elevation.

Actual lake level fluctuations were such that annual surveys beginning in 1973 would have precisely identified any lag in shore response that occurred after the end of the rise in lake levels. Unfortunately, the stations were not surveyed until 1975 (Fig. 15). The measurements that were collected, nevertheless, have some bearing on the proposed lag between lake level changes and shore adjustment. The data points in the emergence region of Figure 15, based on the changes that occurred between August 1975 and September 1976, reveal that shore retreat had abated by that time. Since progradation was not occurring everywhere (see Fig. 8) the shore was probably still in a transition stage in 1976, though it is possible that most of the recession may have occurred shortly after the waters peaked in 1973. Given the available data, the critical question in this regard is whether the recession rates between 1971 and 1975 show a significant reduction below the 1969 and 1971 rates. If so, this would indicate the profiles had nearly regained equilibrium and the hypothesized lag in shore response would probably be shorter than 2 years (the time between the 1973 peak and the 1975 survey).

Given the great variation in rates of recession at different sites, any examination of changes with time should be based on measurements from a common set of survey stations. The inclusion of a single, rapidly retreating station in one period but not the other would drastically influence the difference in the means for the two periods. Recession data are also less variable on the relatively high part of the beach face (see Fig. 9). Using these two considerations, the average recession of the 176.92-meter contour was calculated for the 14 stations which included that contour on surveys for all 3 years. The resulting average rate of recession between 1971 and 1975 was not less, but 37 percent greater than during the previous period. Thus, the mean recession rate measured between 1971 and 1975 increased even though the mean lake level had been falling slowly during the last 2 years of this 4-year period. Rates of recession calculated at the other principal elevations (see Fig. 9) also increased for the 1971-75 period. The reason recession increased is unknown; however, wave activity may have been more intense during this period. Johnson and Hiipakka (1976) report that two unusually destructive storms in the 1972-73 storm season evidently removed 1.5 times as much bluff material as had been eroded during the preceding 2.5 years at the site of a temporary harbor near Bridgman, Michigan, 160 kilometers south of the present study area. The cumulative effect of storm variability in the present study area is unknown, but since recession rates did not decline there is no evidence that the beaches were approaching equilibrium before 1975.

The data are, therefore, consistent with the concept that the shore lags several years behind in its response to the termination of a rapid rise in water levels.

The magnitude of the lag in terms of how much additional shore recession actually occurred between the time when lake levels stabilized and the time when profiles finally equilibrated, can not be calculated directly because there was no survey during the year when levels first stabilized. A good estimate, however, of the "latent recession" (i.e., the response to the inherited stress which was not relieved by profile adjustment until after the lake level had peaked) can be obtained by assuming shore recession continued until the water level peaked in July 1973 at the same rate as existed between 1969 and 1971 (1.91 meters per year). By subtracting the estimated recession before peak levels (1.91 meters per year X 25/12 years = 3.98 meters) from the known recession for June 1971 to August 1975 (14.38 meters averaged from the same stations), the remaining difference (10.6 meters) should be the recession which occurred after the July 1973 peak in order to bring the profiles to the near-equilibrium conditions interpreted for 1975. Given the uncertainties involved, primarily the large variation in recession between stations and the less than desirable timing of peak water levels between widely separated surveys, plus the general nature of the original prediction which was based simply on early profile steepening, the extremely close agreement between the 10.6 meters of calculated recession and the 11 meters predicted must be largely ascribed to chance. The close agreement certainly supports the prediction procedure, but should not be taken as indicative of the precision to be expected with this method. Additional detailed, long-term studies of profiles, which are adjusting to new water levels, and of wave energy variations during the period of adjustment are desirable to refine methods of predicting shore response. In the interim, if it is known that persistent longshore bars have migrated landward faster than the adjacent shore retreated, after some coastal submergence, then it should be assumed that the shore will continue to recede, even after subsidence ceases, until such time as the original spacing between bars and the shore is reestablished.

5. Comparison of Recent and Historic Changes.

The 50-year retreat of the shoreline in the immediate vicinity of Pentwater Harbor was determined by plotting the 1919 shoreline (based on a survey by the U.S. Army Engineer District, Milwaukee) and the 1969 shoreline (based on aerial photos) to a common scale using a zoom-transfer scope. The average shore retreat was then estimated by planimetering the area between the two shorelines and dividing by shore length (450 meters). The 1969 lake level stood 0.46 meter below the 1919 level, so that shore recession was actually greater than shoreline retreat. Therefore, the observed shoreline retreat was reduced by the estimated withdrawal that would have accompanied a decline in water levels to their 1919 elevation. The magnitude of such a withdrawal was estimated using the average profile shape at stations 4.5, 5, 6, and 6.5 in this 450-meter stretch (Fig. 17). The estimated 50-year mean rate of shore recession obtained (see inset in Fig. 17) was 0.30 meter per year. During the 1967-76 period of high water the average rate of recession in this area was only 0.25 meter per year (top part of Table 3). Thus, the rate of recession for this stretch of shore actually decreased during the recent period of high lake levels.

As discussed in Section VI, various influences combine to stabilize the shore in the vicinity of the harbor; consequently, recent rates of retreat near the harbor are not typical of retreat on the adjacent unprotected beaches. It is interesting to note that if measurements had only been made in the vicinity of the harbor, they would have produced no evidence of the increase in recession rates that actually accompanied recent high lake levels. This may be far from an isolated case, because before the present concern for environmental preservation most studies of long-term beach changes on the Great Lakes were conducted near jettied inlets or at sites of critical erosion where efforts were made to stabilize the lakeshore. To the extent that these efforts were effective, they tended to reduce the range of recession rates observed through time and, therefore, to also obscure the correlation between lake levels and shore recession.

One data set which does not concentrate on areas of critical erosion was compiled by Powers (1958) who resurveyed a part of the shore bluff near section corners along most of the entire perimeter of Lake Michigan. Two of his stations which fall within the present study area are shown as P85 and P86 in Figure 4; two more stations were located just south of the study area, 4 and 15 kilometers, respectively, from station 29. The rates of bluff recession at these four points between 1838 and 1957 averaged

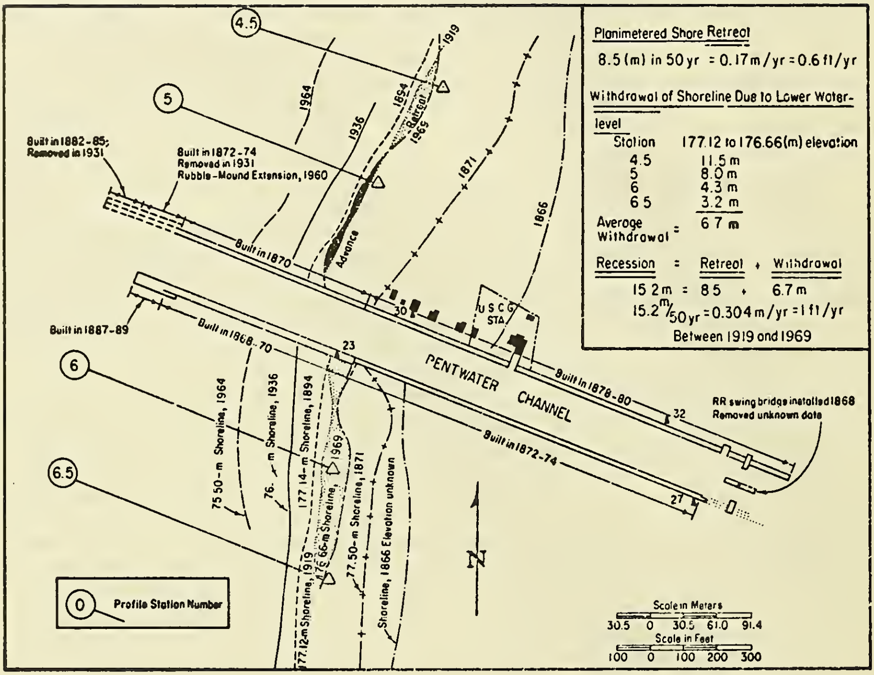


Figure 17. Historic shoreline changes in the vicinity of Pentwater Harbor. A 50-year recession rate of 0.3 meter per year was calculated using 1919 and 1969 shoreline positions and correcting for withdrawal of the lake away from the shoreline due to lower lake levels in 1969.

Table 3. Comparison of historic with recent recession rates.

Historic	Recent
Area extending 200 meters to either side of the Pentwater jetties	
Planimetered aerial photos adjusted for encroachment (1919 - 1969) Progradation on the north side of the jetties; recession on the south side.	Surveyed recession at four stations (1967 - 1976) Progradation on the north; recession on the south.
Avg. recession rate: 0.30 m/yr	0.25 m/yr
50-kilometer study area, excluding sites of extensive modification by man	
Surveyed bluff recession (1838 - 1957) Power's (1958) stations — Net recession (m) 85 — 35 86 — 65 87 — 66 88 — 39	Surveyed shore recession at 14 stations monitored from 1969 - 1975
Avg. recession rate: 0.43 m/yr	2.54 m/yr

0.43 meter per year, compared to a 2.54-meter per year average rate for profile stations between 1969 and 1976. Stations where bulkheads had been installed were omitted in the determination of the recent recession rate. Property owners also made a variety of other attempts to reduce erosion at many of the remaining stations, but these efforts apparently had only a minor effect and measurements from such stations were retained in the calculation of the recent recession rate. The 2.54-meter per year rate is, therefore, an estimate of the recent rate recession on a relatively unprotected shoreline. The older historic measurements also reflect natural recession, unaffected by man's interference.

The recent recession rate of more than six times the historic average reflects the effect of high lake levels in accelerating shore erosion. The 1969-75 period represents the most intense phase of erosion during a lake level cycle, whereas the 119-year rate includes the effects of several episodes of both high and low levels (Fig. 2).

Four measurement stations do not constitute a large sample on which to base an estimate of long-term recession rates for this 60-kilometer stretch of shore; however, each measurement does cover a 119-year period, and variations in retreat rate do decrease as the period of observation increases (see Fig. 14). In fact, these four measurements are about as efficient for estimating the long-term mean rate as the larger number of measurements made during this investigation are for estimating the shorter term mean rate. The difference between bluff and shore erosion over the 50-year period should be inconsequential compared to the 600-percent increase in recession during the recent period of high water.

The four historic measurements near the present study area, and other available information on historic rates along Lake Michigan's eastern shore are shown in Figure 18. These historic rates are based on net changes in bluff position surveyed in the 1830's and again in the 1950's (Powers, 1958). Over such a long period of time the error involved in assuming equilibrium becomes small; i.e., recession of the bluff tends to approach recession measured at any other point on the upper profile in the sense that any differences become small relative to the total displacement of the profile (in this case an average of 52 meters).

The relatively uniform low rates of historic recession along most of the eastern shore further indicate that the estimate of 0.43 meter per year cannot be too far from the true rate of historic recession for the present study area.

Changes in the rates of shore retreat between various time intervals at severely eroding localities on Lake Michigan are given by Seibel (1972) and by Hands (1976). Net changes presented in those references were measured over periods of several years; some periods coincided with episodes of high water, others with episodes of low water. The rates of successive periods at given locations commonly varied by 200 to 600 percent.

Thus, although the surveys for this study covered only a part of a lake level cycle, sufficient historic evidence is available to indicate

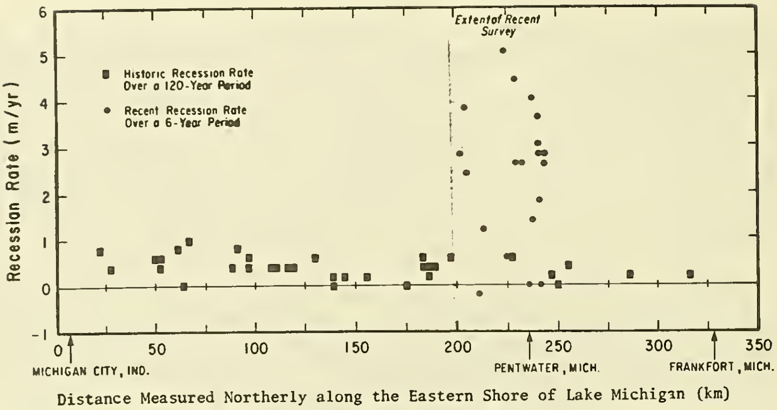


Figure 18. Comparison between rates of historic (1830's to 1959's) and recent (1969-75) recession. Positions of survey stations on the eastern shore of Lake Michigan are referenced to the Porter-La Porte County boundary in Indiana.

that recession rates during the period of rising water rose to six times their longer term average.

6. The Need to Adjust Recession Rates.

The large temporal changes observed in recession rates make it difficult to determine a "natural erosion rate" to be expected for a given beach on the Great Lakes. Changes in the mean recession rate by a factor of 3 to 4 after some intervention by man (which may be related to shore protection, etc.) can not definitely be ascribed to that intervention, unless the water levels were essentially the same before and after the action in question. An untested general rule for comparing recession rates determined under different water level conditions would be to subtract a factor presumably attributable to the difference in lake levels from the "after-action" recession rate. Figure A-1 in Appendix A can be used as a guide for determining this factor. If the resulting "adjusted estimate" does not differ substantially for the "before-action" rate, then the conservative conclusion would be that there is insufficient evidence to establish whether the action in question played any part in increasing recession rates.

This approach would be most directly applicable when the lake level has changed from stable to rising. If the before-action survey interval ends about the time the rise in lake levels ends, then it should be remembered that the recession rates may remain high in response to that rise for several years until erosion has brought the profile back into adjustment. As the effects of high water may persist into the after-action survey period, the full "correction factor" should not be applied unless the shore has regained equilibrium. Examples are given in Appendix A.

More study is needed on profiles returning to equilibrium under constant water levels to establish procedures for estimating the adjustment time, and also to establish the outer limit of the responding profile as this factor controls the physical work required to adjust the profile after perturbation by a lake level change.

VI. CONCLUSIONS

When water levels rise or a coast subsides, shorelines tend to retreat. Retreat in response to submergence is particularly important on the Great Lakes where climate and hydrologic variations cause significant water level fluctuations. The process of shore retreat and eventual stabilization is examined by using beach profiles obtained at 34 stations surveyed in 1967; 1969, 1971, 1975, and 1976 on the eastern shore of Lake Michigan.

The annual mean elevation of Lake Michigan during this century has gone through several cycles during which water levels rose for several years in succession (e.g., 1964-73), and then declined for a similar period. However, the net rate of shore recession during the last 100 years is small relative to the rates measured during the end of the recent rising phase. Landward sand transport and shoreline accretion during the intervening years of declining lake levels cause the shore to advance, thus lowering the overall historic recession rate. The mean water level elevation is the principal factor establishing a potential erosion rate for a given shore type; the extent of erosion actually realized will then depend on the available energy. The actual retreat of the shore can be divided into two components: (a) encroachment of the water due to submergence of the beach, and (b) recession due to erosion as the beach adjusts to the new water surface elevation. Given a change in water level, the encroachment can be predicted exactly; the recession, which may be several times more important in terms of ultimate shore retreat, can only be crudely predicted at present.

After a rise of 0.8 meter in annual mean lake level between 1967 and 1973, recession rates remained well above the historic average through 1975. By the fall of 1976, however, shore erosion had ceased at most survey stations. After retreating an average of 24 meters from 1967 to 1975, the shore may have finally regained approximate equilibrium with the (by then) slowly falling mean water surface.

Large variations in retreat were observed at adjacent stations. Areas on Little Sable Point and at the south end of the study area suffered the greatest net retreat; the area in the immediate vicinity of the Pentwater jetties suffered the least. Less loss around the jetties reflects the effects of various shore protection measures employed there. An explanation for the generally high rate of retreat in the other areas is not evident at this time.

The spread of retreat rates among the different stations decreased as time progressed through the study period. This trend shows that only a few profile lines need to be resurveyed after an elapse of many years to provide an estimate of the long-term retreat rate, which is equally as efficient as an estimate of a short-term rate based on a larger number of profiles. The 119-year rate of recession based on four stations originally surveyed in 1838 was 0.43 meter per year. The rate of recession between 1969 and 1975 (based on measurements at 20 stations) was more than five times greater than this historic average. This acceleration of recession was brought on by the recent high water levels.

The correlation between water levels and recession rates is poorly defined at localities where shore protection measures are adopted at times of greatest potential loss; however, data from the relatively undisturbed stations monitored in this study show that shore recession was roughly proportional to the increase in water levels. Although local variation was considerable, the shore retreated on the average of 4 meters for each 0.1 meter of submergence.

Surprisingly, this 40 to 1 ratio also gives a good approximation to the average advance of the shoreline as water levels declined during the last year of the study. Encroachment of water on the shore as lake levels rise causes only a small part of the total retreat of the shoreline. Erosion and accretion are nearly an order of magnitude more important than encroachment in terms of how far the shore is actually displaced. The period of adjustment following a change in the mean water level elevation may last for several years depending on the magnitude of the water level change, the type of beach material, the geomorphology of the shore, and the availability of wave energy to redistribute material. The capability to generalize recession predictions will improve when the balance of sediment volumes shifting back and forth over the entire active profile is better understood.

Recession of a particular contour is one convenient way of expressing the amount of shore erosion. The actual contour or elevation selected, however, will affect the outcome, and all contour changes do not give equally representative estimates of the regional recession. In this study, all recession lines significantly above the lowest water level gave relatively good indications of at least the *regional pattern* of shore recession; however, measurements at the higher elevations more efficiently estimated the actual *mean* recession for a stretch of shore. Recession lines near and below lake level not only were inefficient as estimates of the mean recession for the area, but also failed to reveal even the general pattern of regional shore retreat. This is because lower contours may prograde lakeward while the higher beach face is eroding. In general, to obtain stable and reliable estimates of recession from a few measurements, the measurements should be taken where the beach profile slopes steeply so that small changes in elevation do not cause large changes in contour position.

The effect of water level changes on recession must be considered if historic changes in the rate of shore retreat are to be properly ascribed to other causes. A graph of the retreat that accompanied sumbergence is given in Figure A-1 which can be used as a guide to determine whether observed changes in retreat rates measured after a given event are actually due to that event, or might more simply be attributed to the different water levels during the interval between surveys.

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APPENDIX A

A PROCEDURE FOR ADJUSTING RATES OF SHORE RETREAT TO COMPENSATE FOR WATER LEVEL DIFFERENCES

1. Problem.

The rate at which a particular beach retreats will depend on interactions among a large number of factors. These factors can be grouped into categories, such as (a) the characteristics of littoral materials that determine their mobility or resistance to erosion, (b) the intensity of waves and currents, and (c) the degree to which the littoral materials are in or out of adjustment with the potentially erosive forces. Sometimes the activities of man can have a drastic and obvious influence on retreat rates. In other instances man's impact, though substantial, is difficult to assess because it cannot be isolated from the total effect due to the interaction of many varying but poorly known factors.

It is well known that a long-term increase in water levels on the Great Lakes promotes rapid shore retreat. There have been a number of attempts to quantify certain aspects of the relationship between lake levels and erosion (Beach Erosion Board, 1946; Davis, 1976; Berg and Collinson, 1976). Because water levels are always varying on the lakes, it would often be helpful if the effect of water levels on erosion rates could be removed from measured rates so that the impact of the other factors would be clearer. The following is a description of how shore retreat measurements made on eastern Lake Michigan between 1969 and 1976 can be used to estimate the minimum amount of shore retreat in response to various lake level changes.

2. Data.

The data base consists of shoreline changes measured over 1- to 6-year intervals at 33 stations along a 50-kilometer reach centered on Little Sable Point, Lake Michigan. Station locations, survey dates, and lake level elevations are described in the text. Figure A-1 gives an estimate of the mean shoreline change due to the long-term net differences in lake levels. Figure A-1 is similar to Figure 15 except (a) measurements made within 1 kilometer of Pentwater are deleted as unrepresentative of the natural processes on an unobstructed coast, and (b) all measurements of shoreline retreat have been reduced by 3 meters (the residual retreat presumably not due to any water level effect) so that the predicted response is zero when there is no water level change.

The amount of recession is a function of many factors. Submergence explains roughly half the variance in the test data. The mean shore response to submergence by a given amount will probably fall within the bounds shown in Figure A-1. These bounds indicate the nominal 95-percent confidence limits for the mean recession based on a least squares fit ($r = 0.75$) to the 105 data points. The fact that most of the points fall outside the confidence band illustrates the greater difficulty of

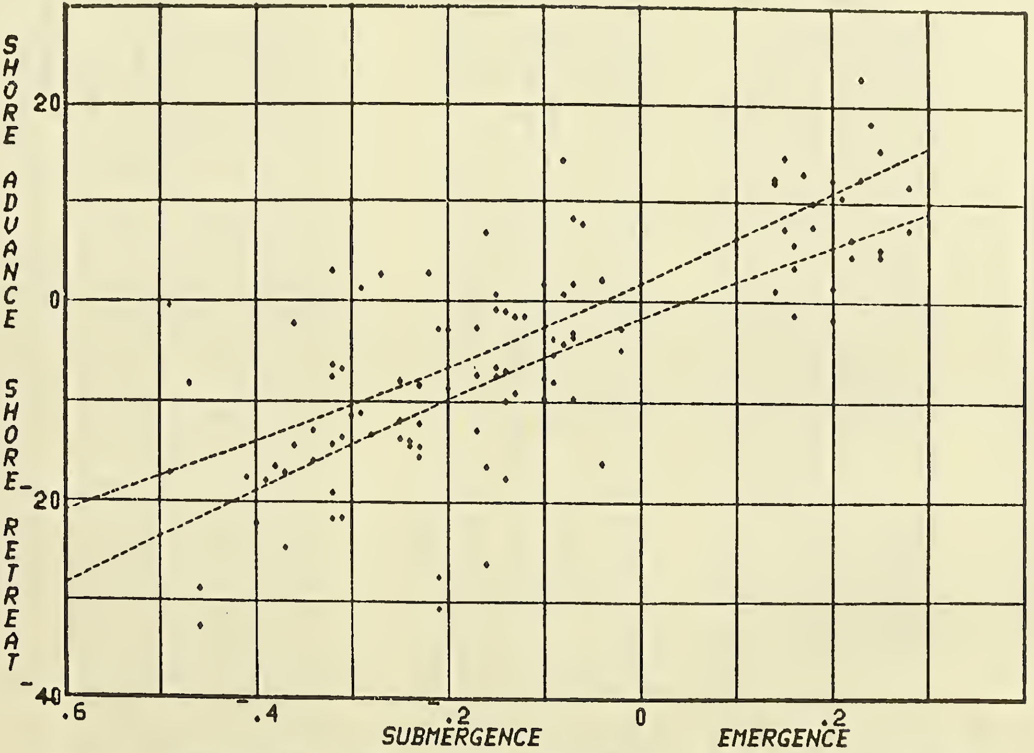


Figure A-1. Shore retreat as a function of different amounts of submergence. Both measurements are in meters. The dashlines serve as a guide for estimating the mean shore response in certain situations (see text).

predicting recession at a single point as compared to predicting the mean recession along some stretch of shore. The curves in Figure A-1 are intended to serve as guides for making a conservative estimate of the mean response due solely to lake level changes, as illustrated in the following examples. Because the assumptions required to make a strict statistical inference may not be justified, the curves are not intended to support probability-like statements as to exactly how reliable such a correction would be. Reference to the upper or lower curve simply indicates a safe or conservative interpretation. In some cases, as in example 1 below, this will be sufficient basis for a decision.

3. Engineering Application.

Two examples are given to illustrate applications of Figure A-1 to field problems.

a. Example 1 - Has a Coastal Project Increased Erosion on An Adjacent Beach? The effect of a project on shore erosion, and the extent of its influence in an alongshore direction are uncertain. Assume that during the 50-year period just before the project, the shore retreated 150 meters (for an average rate of 3 meters per year). In the 4 years since completion of the project, the same stretch of shore receded 24 meters (6 meters per year; Table A-1). Further assume these rates are well established by measurements at a number of points along a particular beach. Do these data provide clear evidence that the project accelerated erosion on that beach? If so, is the difference in retreat (3 meters per year X 4 years = 12 meters) a reasonable estimate of the beach loss caused by the structure?

Table A-1. Data and adjustment for example 1.

Earlier survey interval		Later interval
Retreat	150	24 m
In	50 yr	4 yr
Rate	3 m/yr	6 m/yr
Measured retreat	150	24 m
Adjustment	-0 m	-14 m
Remaining retreat	150 m	10 m
Adjusted rate	3 m/yr	2.5 m/yr

Suppose that lake levels began rising a few years before project completion, and during the 4-year survey period after construction the annual mean lake level rose 0.4 meter. The preceding 50 years had been marked by several cycles of rising and falling water levels with no significant net change in lake level elevation. (Such conditions would not be unusual on the Great Lakes.) The higher water levels certainly played some role in increasing shore retreat during the latter period. Can the amount of additional erosion due to high water be estimated?

Assuming the response of the shore will be directly proportional to the amount of water level change, and that the retreat measured on the eastern shore of Lake Michigan can serve as a guide in the present situation, Figure A-1 suggests 14 to 19 meters of retreat occurs in response to 0.4 meters of submergence. It is expected that individual measurements from points up and down the problem beach would show greater variation as indicated by the scatter of points beyond the confidence band for the mean in Figure A-1. However, at least 14 meters of retreat would be a conservative estimate of the *mean* response due solely to the increased lake level; it is the mean response which is of concern here. Assuming the overall conditions of the problem site are similar to those around Little Sable Point (as indicated by similarities in sand size, nearshore bathymetry, wave exposure, etc.), the estimated lake level effect is subtracted from the measured postproject retreat, and the resulting adjusted rate becomes (24 minus 14 meters = 10 meters in 4 years) 2.5 meters per year. The adjusted recession rate is even less than the historic average before the project (Table A-1). Thus, the increase in lake levels is more than enough to explain the observed increase in shore retreat. There is no evidence that the project itself resulted in any increased shore retreat. In this example many variables that may have influenced the rates were not measured, so it is still possible that the project itself tended to increase erosion and that this tendency was overshadowed by other factors. However, once adjusted, the available recession rates are not sufficient to suggest the project has had any detrimental effect on the beach in question.

b. Example 2 - Evaluating a Shore Protection Device. The second hypothetical case involves the determination of how well a shore protection device has performed. The device was installed along a shore which had experienced erosion during a recent period of high water. The average beach width had decreased 40 meters in 7 years. Lake levels had risen 0.4 meter during the first 5 years, but had remained stable during the 2 years just before installation of the shore protection device. The project was monitored for 2 years after installation, and no further shore retreat was observed. Based on this information, how well did the device seem to perform?

Again, Figure A-1 suggests that the average distance the shore would have receded in adjustment to the 0.4-meter increase in lake level is from 14 to 19 meters. Subtracting this from the measured average retreat leaves 21 to 26 meters unexplained (Table A-2). A conservative claim would be that even after taking water level differences into account, the

Table A-2. Data and adjustment for example 2.

Earlier survey interval		Later interval
Retreat	40 m	0
In	7 yr	2 yr
Rate	5.7 m/yr	stable
Measured retreat	40 m	
Adjustment	-19 m	No change in mean water level
Remaining retreat	21 m	No retreat
Adjusted rate	3 m/yr	0 m/2yr

rate of shore retreat seems to have decreased from 3 meters per year during the 7 years before installation to zero after the device was installed. The question would then be whether the 2-year monitoring period included representative conditions, or whether any other factors during that period could have been responsible for the reduced erosion, and whether the apparent benefits outweigh the known costs.

4. Discussion.

Figure A-1 can at best help the engineer to evaluate one factor in what would probably be a multifaceted problem. If this important factor is taken into account by extrapolation from actual measurements, the other items can then be dealt with in their usual manner.

The data in Figure A-1 are estimates of actual retreat during a period of submergence. The actual retreat may be less than the ultimate retreat necessary to reestablish equilibrium, both because of conditions under which the data were collected and the simplistic manner in which the data were analyzed. In the use of Figure A-1, lake level changes and shore response should refer to net displacements over periods on the order of 2 to 10 years. The applicability of Figure A-1 will also depend on the degree of similarity between the problem site and the site where data for Figure A-1 were collected. The environmental summary at the end of this appendix will assist the engineer in comparing the problem area to the present site.

If a significant difference between sites exists, then the qualitative effect this would have can be determined by considering sediment balance. If the problem site has a deficiency of sand-sized material in the backshore, either because of low relief or the preponderance of very fine grained material, then the retreat required to reestablish equilibrium, with a unit increase in lake level, will be greater than Figure A-1 indicates. The same will be true if there are longshore or offshore sediment sinks, or if the active profile is broader than in the study area. More turbulence or lower nearshore gradients would increase the breadth of the active profile and the anticipated retreat. Conversely, less retreat than predicted in Figure A-1 would be expected when the problem area has a narrower active profile, higher or coarser backshore sand deposits, or a net inflex of sediment from external sources.

5. A Summary of Environmental Conditions in the Study Area.

The shore throughout the study area consists of unconsolidated deposits. As along most of the eastern shore of Lake Michigan, the shore type alternates between sections of morainal bluffs and dune-covered plains. During the study, waves primarily attacked modern foredune ridges which were present even where bluffs of glacial drift formed the backshore. The presence of a shallow stiff clay was observed at a couple of points of exposure both onshore at the base of bluffs and offshore along the deeper sections of troughs between longshore bars. These scattered clay outcrops are the most resistent formations in the study area. One of the more extensive areas of actively migrating dunes on the Great Lakes marked the central part of the study area (see Figs. 4 and A-2). Examples of shore forms throughout the study area are shown in Figures 12, A-3, and A-4. Shore profiles at each station are shown in Appendix B. A typical nearshore profile is shown in Figure A-5; details of nearshore geometry are described in Hands (1976). In considering the likely differences in response to high water on two separate beaches, the shape of the nearshore profile may be the single most important comparison, since it reflects aspects of both the level of turbulence which the coast is exposed to and the materials of which it is composed.

Figure A-2. Aerial view looking across Little Sable Point from Lake Michigan toward Silver Lake. Profile station 14 is in the right foreground.

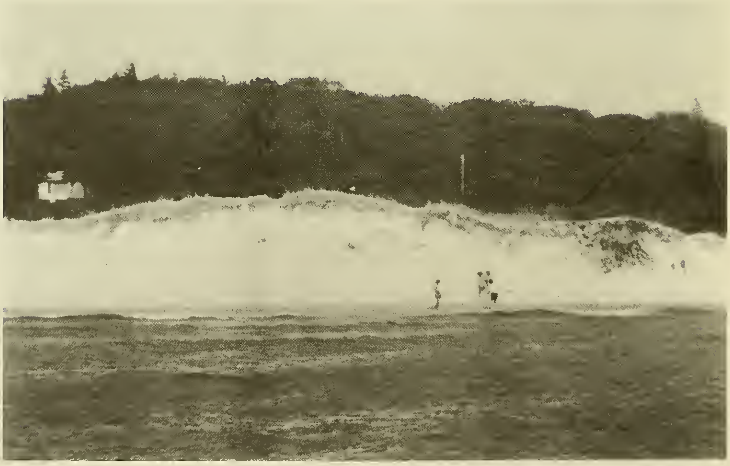
Where glacial bluffs are being eroded by direct wave attack, several kilometers north of the study area, gravel and cobbles are prominent on the upper beach. Throughout the study area, however, the beaches are sandy with a mean grain size in the upper 2 centimeters of the swash zone ranging from 1 to 2.5 phi (0.50 to 0.18 millimeter). Longshore trends in mean grain size on the beaches are mirrored by similar trends in the finer sands along the crests of the longshore bars. Additional factors representative of conditions in the study area, and references to more detailed descriptions are itemized in Table A-3.

Station 3.5, September 1976.

Station 16, September 1976.

Figure A-3. Wave erosion of foredunes resupplies the beach with more well-sorted fine sand. Counterclockwise from the upper left, surveyors measure profiles at stations 3.5, 16, 13, and 22.

Station 13, August 1975.



Station 22, September 1976.

Figure A-3. Wave erosion of foredunes resupplies the beach with more well-sorted fine sand. Counterclockwise from the upper left, surveyors measure profiles at stations 3.5, 16, 13, and 22--Continued.

Figure A-4. The top photo shows a 65-meter-high bluff (behind profile station 25) which is composed primarily of sand, but was protected from wave attack during the study period by a narrow beach and foredune that survived this period of erosion. The lower photo shows the highest dune undermined by wave erosion. By 1976, the unstable slip face extended almost to the top of this 37-meter-high dune at profile station 19.

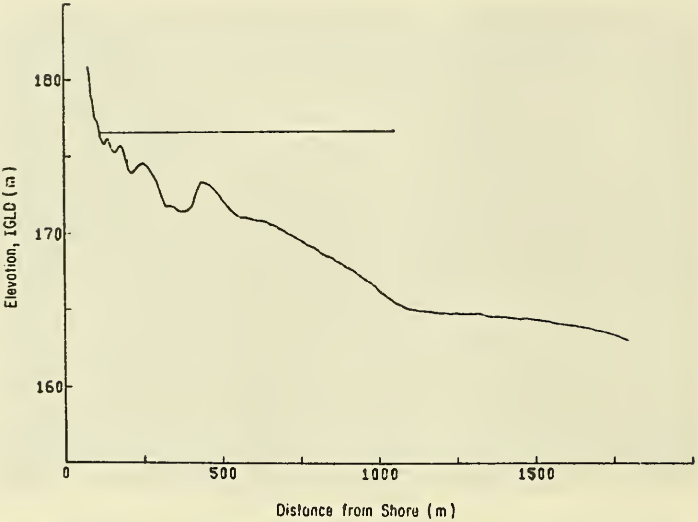


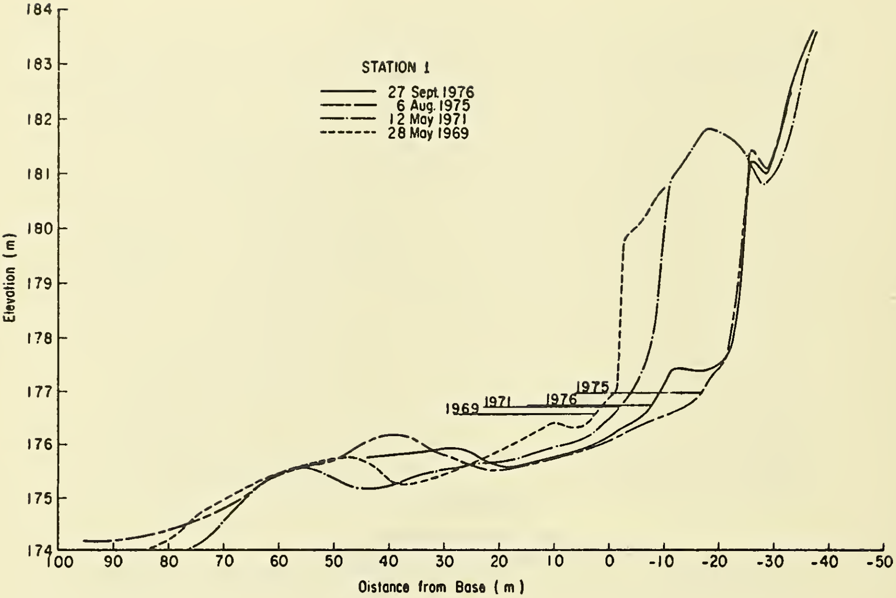
Figure A-5. A typical example of the nearshore bathymetry in the study area.

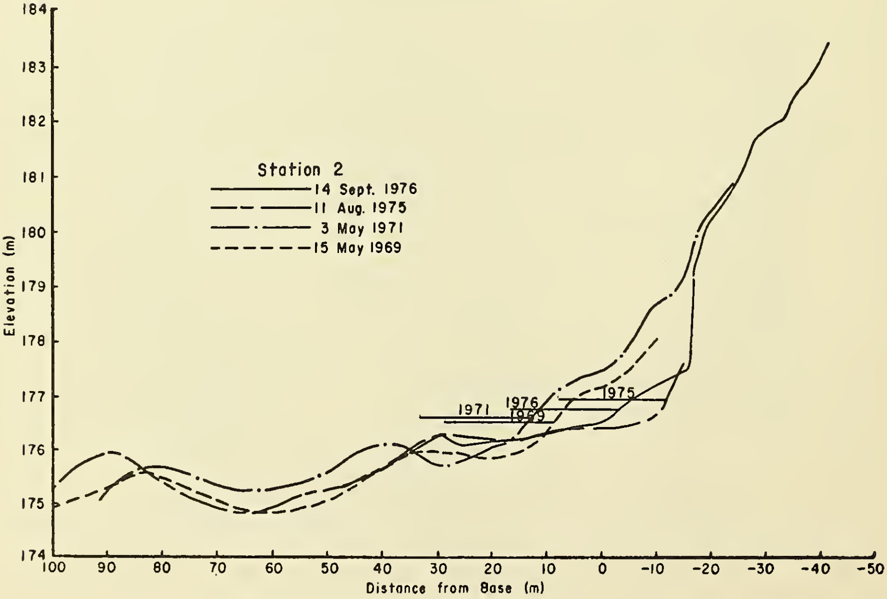
Table A-3. Environmental parameters in the study area.

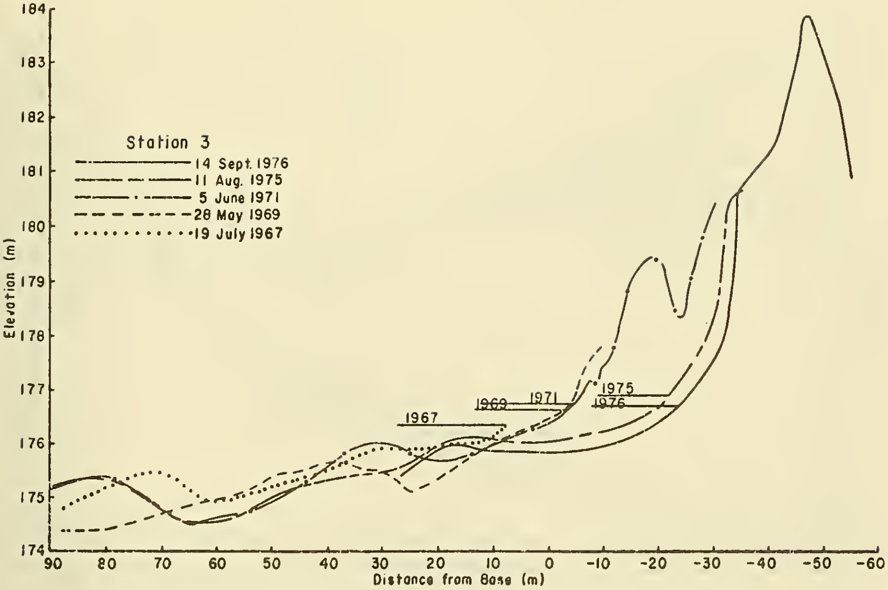
Factor	Parameters	References
Nearshore bathymetry		
Distance of the 10-m isobath from shore	800 to 975 m	Hands (1976)
Number of persistent longshore bars	4 to 5	
Distance of outer bar from shore	300 to 500 m	
Depth over the crest of the outer bar	4 to 6 m	
Surface grain-size distribution		
In the swash zone	$1 \le M_\phi \le 2.5$	Hands (1976)
	$0.3 \le S_\phi \le 0.5$	
On the crest of the third bar	$2 \le M_\phi \le 2.7$	
	$0.3 \le S_\phi \le 0.5$	
From backshore dunes	$1.7 \le M_\phi \le 2.5$	
	$0.3 \le S_\phi \le 0.4$	Hulsey (1962)
Wave climate		
Wave height exceeded once per month	2.3 m	Saville (1953)
Wave height exceeded once per year	4.0 m	
Wave height exceeded once per 5 years	5 to 5.5 m	Resio and Vincent (1976)

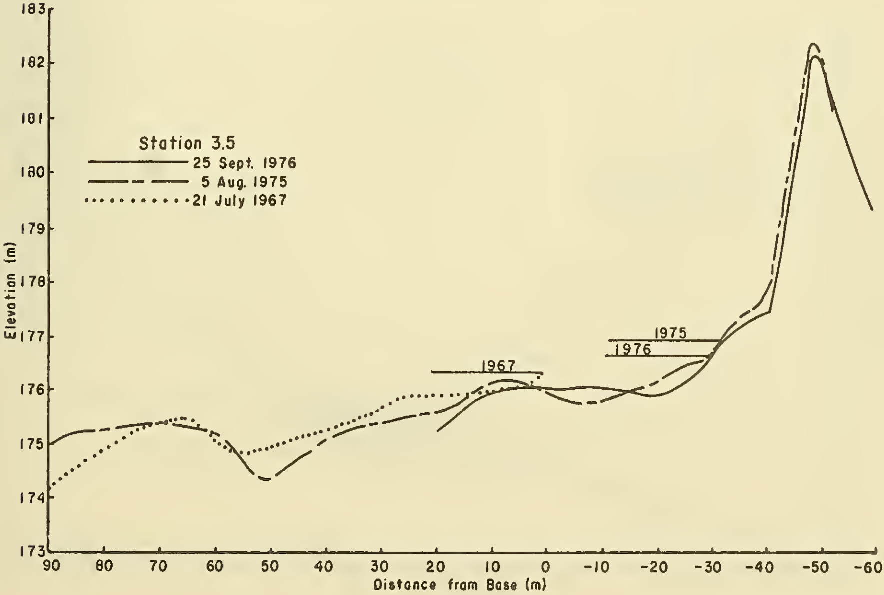
APPENDIX B

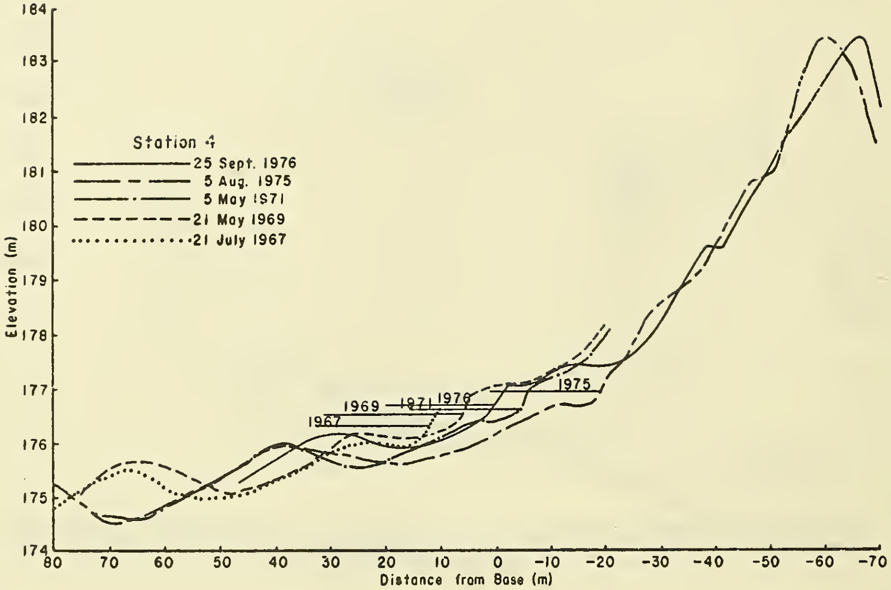
NEARSHORE PROFILE CHANGES

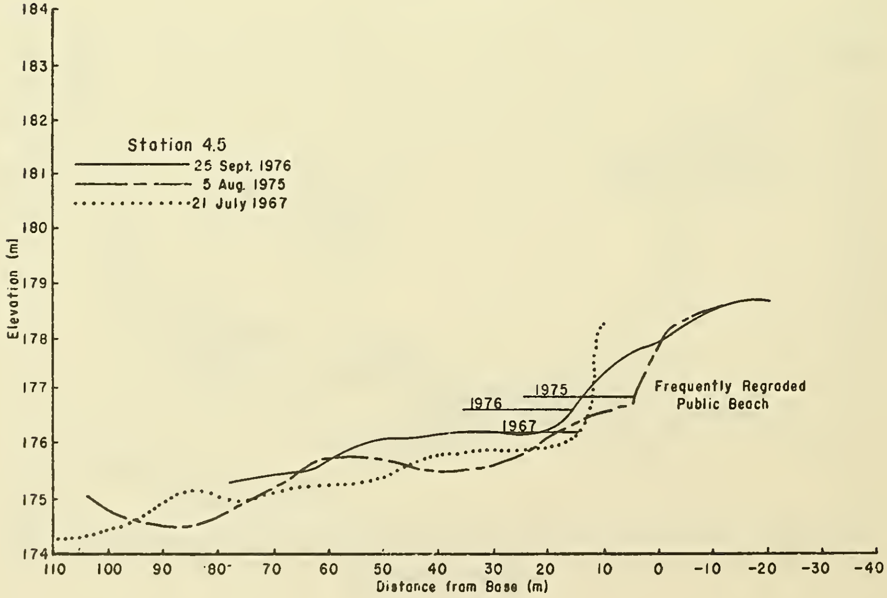

STATION 1
27 Sept. 1976
6 Aug. 1975
12 May 1971
28 May 1969
1969
1971
1976
1975
Elevation (m)
184
183
182
181
180
179
178
177
176
175
174
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

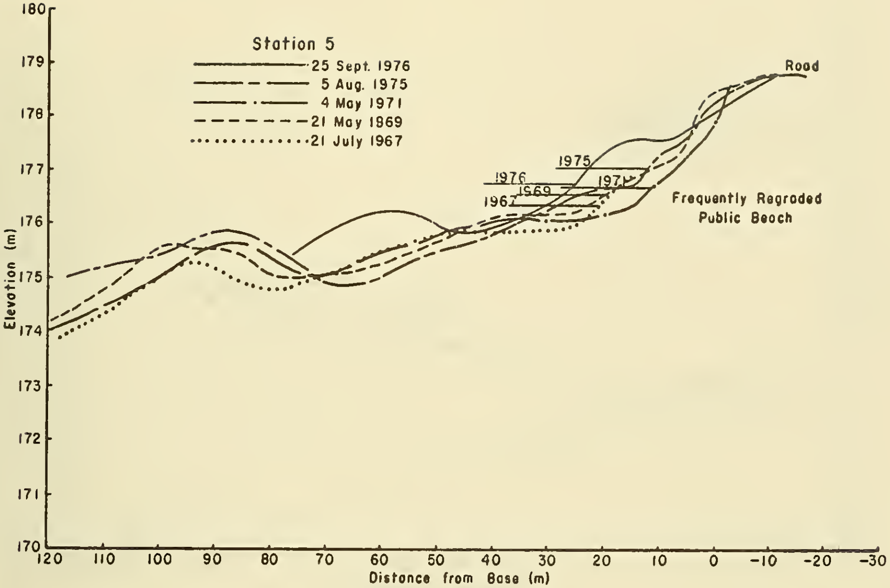

Station 2
14 Sept. 1976
11 Aug. 1975
3 May 1971
15 May 1969
1971
1976
1969
1975
Elevation (m)
184
183
182
181
180
179
178
177
176
175
174
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

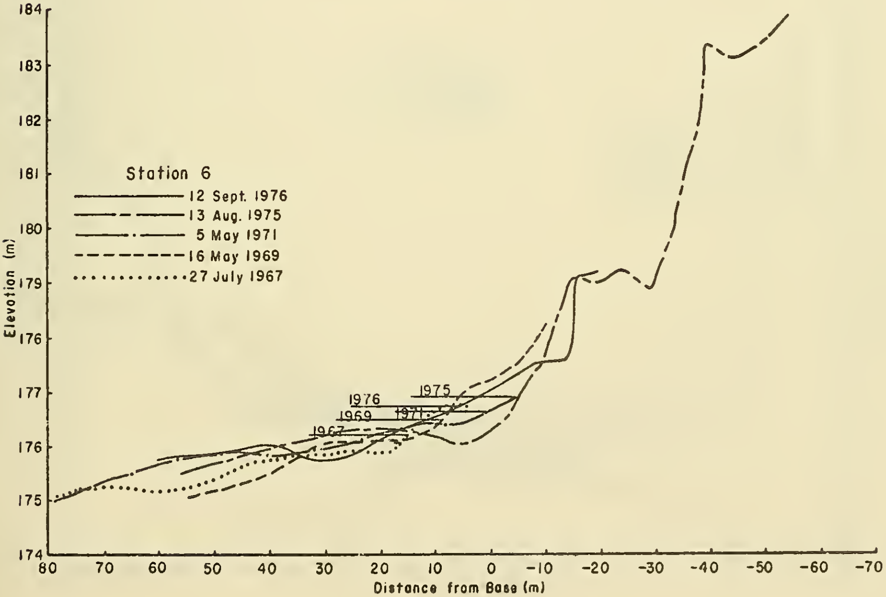

Station 3
14 Sept. 1976
11 Aug. 1975
5 June 1971
28 May 1969
19 July 1967
1967
1969
1971
1975
1976
Elevation (m)
184
183
182
181
180
179
178
177
176
175
174
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
Distance from Base (m)

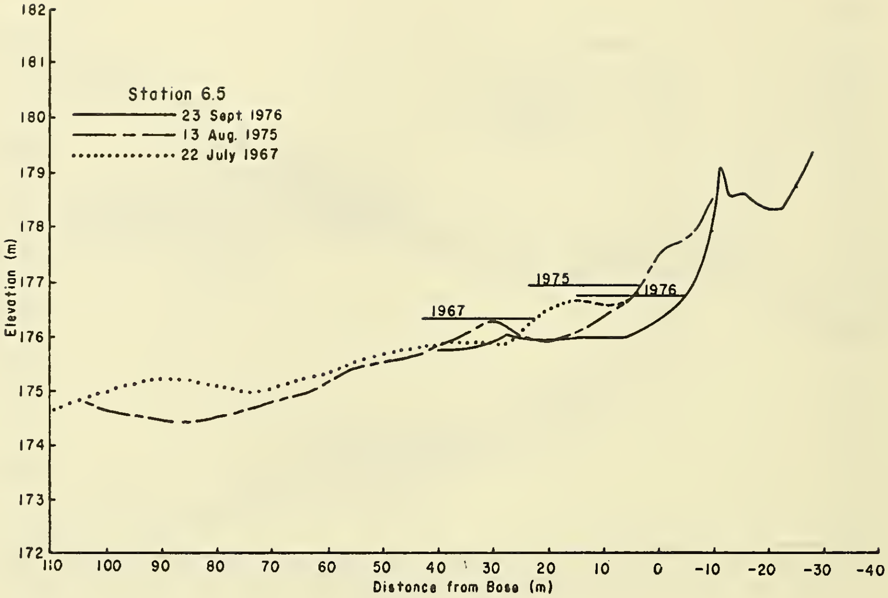

Station 3.5
25 Sept. 1976
5 Aug. 1975
21 July 1967
1967
1975
1976
Elevation (m)
183
182
181
180
179
178
177
176
175
174
173
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
Distance from Base (m)

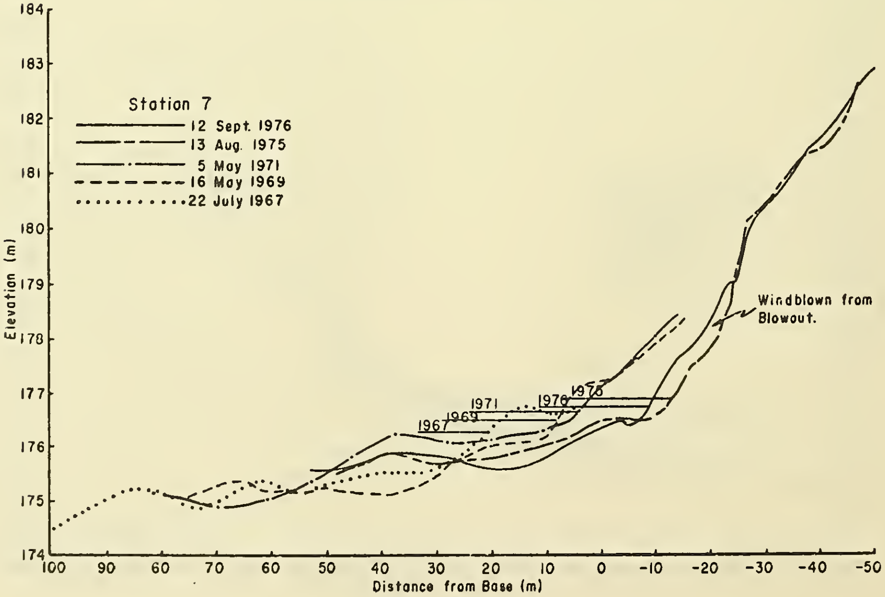

Station 4
25 Sept. 1976
5 Aug. 1975
5 May 1971
21 May 1969
21 July 1967
1975
1976
1971
1969
1967
Elevation (m)
174
175
176
177
178
179
180
181
182
183
184
Distance from Base (m)
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70

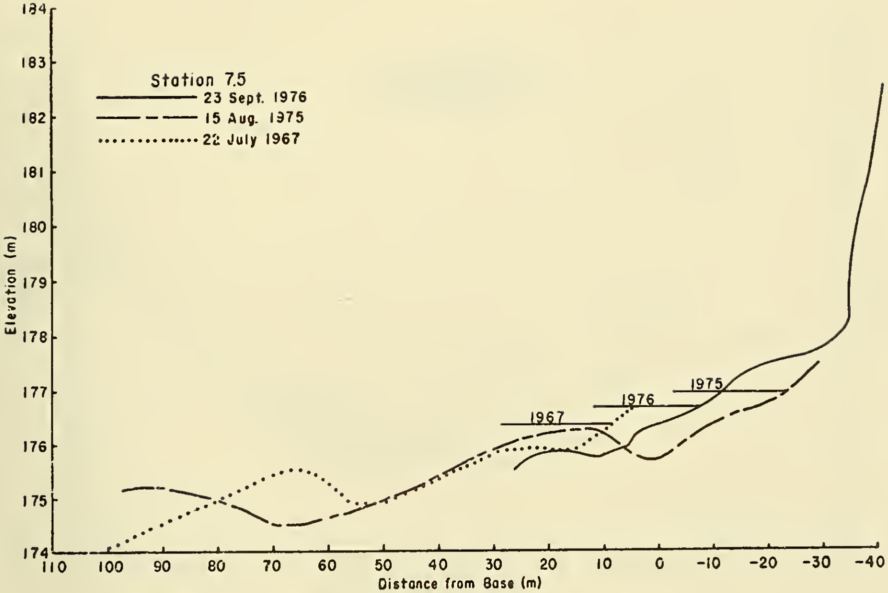

Station 4.5
25 Sept. 1976
5 Aug. 1975
21 July 1967
1975
1976
1967
Frequently Regraded Public Beach
Elevation (m)
174
175
176
177
178
179
180
181
182
183
184
Distance from Base (m)
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40

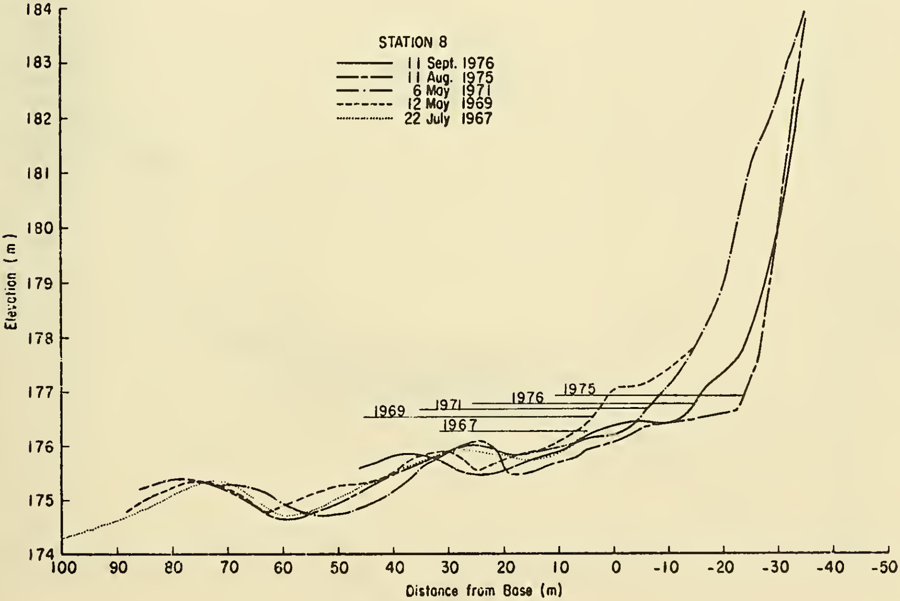

Station 5
25 Sept. 1976
5 Aug. 1975
4 May 1971
21 May 1969
21 July 1967
Road
1975
1976
1971
1969
1967
Frequently Regraded Public Beach
Elevation (m)
180
179
178
177
176
175
174
173
172
171
170
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
Distance from Base (m)

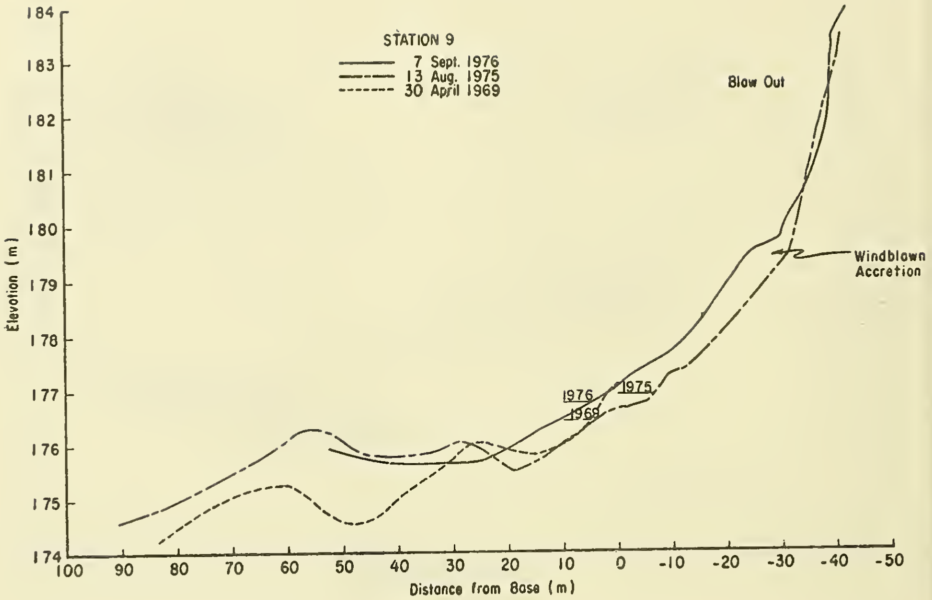

Station 6
12 Sept. 1976
13 Aug. 1975
5 May 1971
16 May 1969
27 July 1967
1975
1976
1971
1969
1967
Elevation (m)
184
183
182
181
180
179
176
177
176
175
174
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
Distance from Base (m)

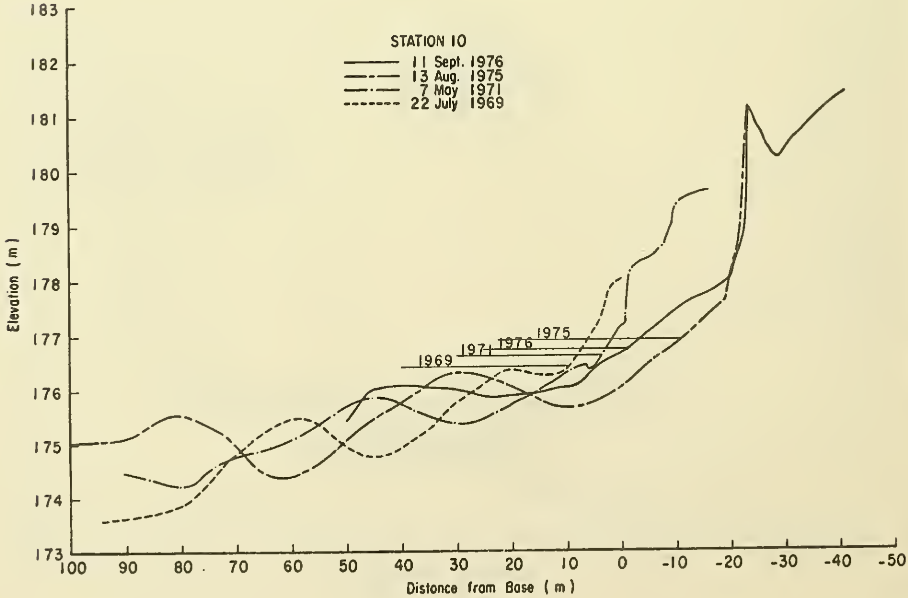

Station 6.5
23 Sept. 1976
13 Aug. 1975
22 July 1967
1975
1976
1967
Elevation (m)
182
181
180
179
178
177
176
175
174
173
172
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
Distance from Base (m)

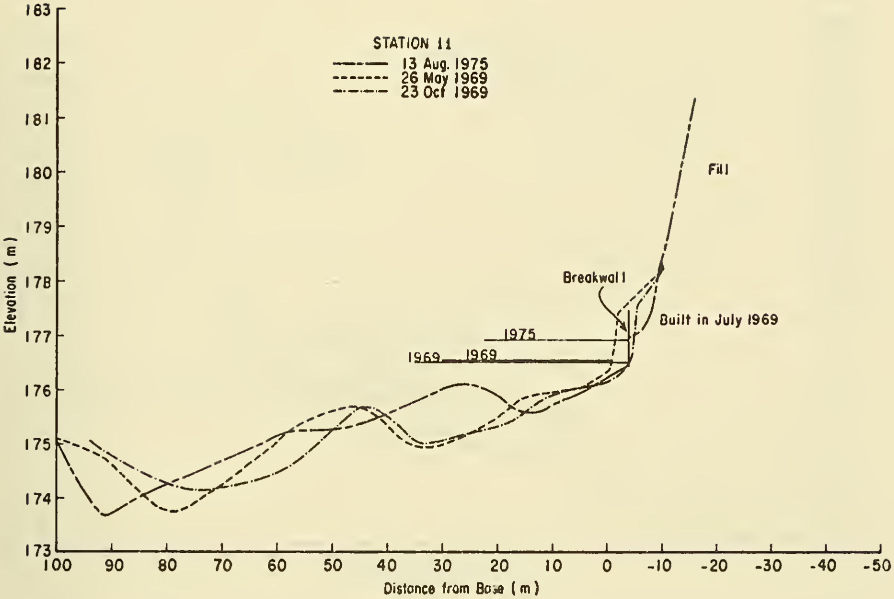

Station 7
12 Sept. 1976
13 Aug. 1975
5 May 1971
16 May 1969
22 July 1967
1971
1969
1967
1976
1975
Windblown from Blowout.
Elevation (m)
184
183
182
181
180
179
178
177
176
175
174
100
90
60
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

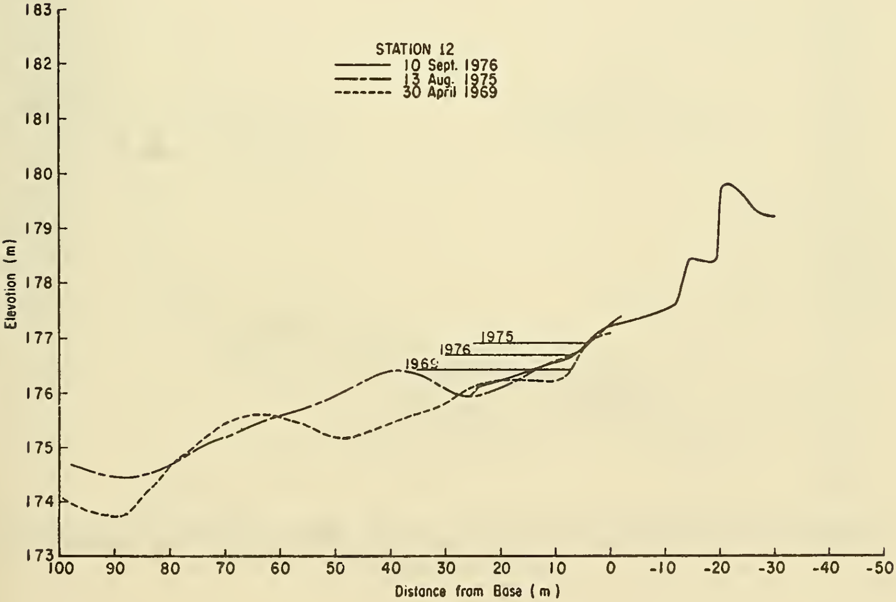

Station 7.5
23 Sept. 1976
15 Aug. 1975
22 July 1967
1975
1976
1967
Elevation (m)
184
183
182
181
180
179
178
177
176
175
174
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
Distance from Base (m)

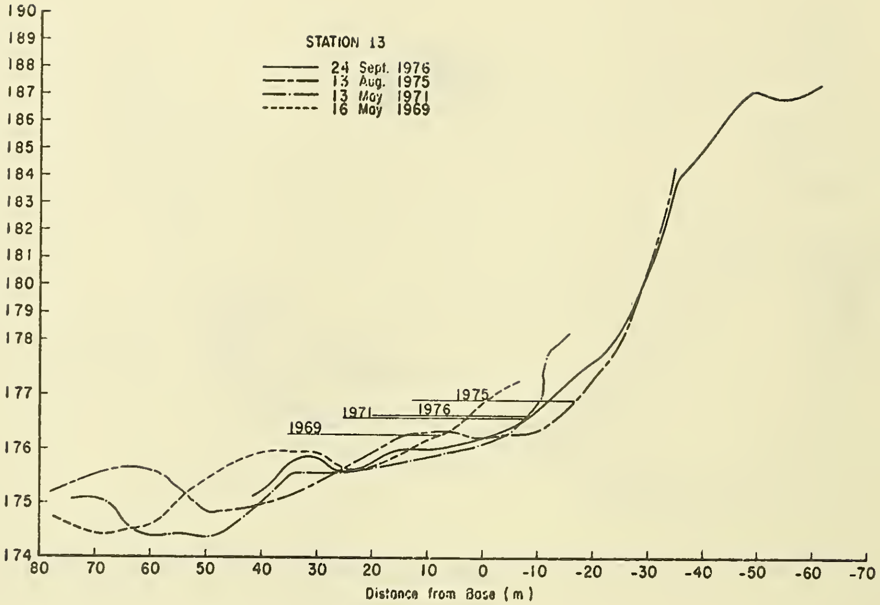

STATION 8
11 Sept. 1976
11 Aug. 1975
6 May 1971
12 May 1969
22 July 1967
1975
1976
1971
1969
1967
Elevation (m)
184
183
182
181
180
179
178
177
176
175
174
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

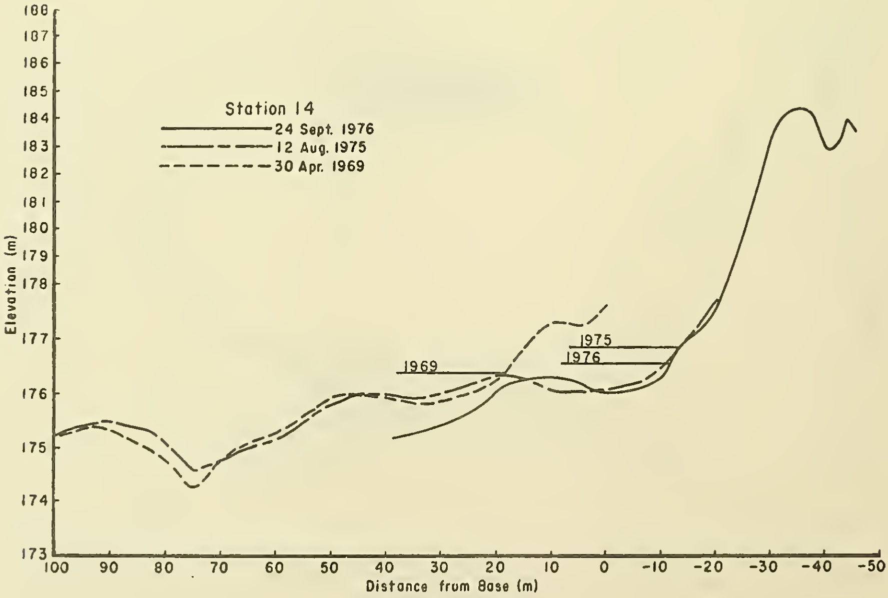

STATION 9
7 Sept. 1976
13 Aug. 1975
30 April 1969
Blow Out
Windblown Accretion
1976
1975
1969
Elevation (m)
184
183
182
181
180
179
178
177
176
175
174
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

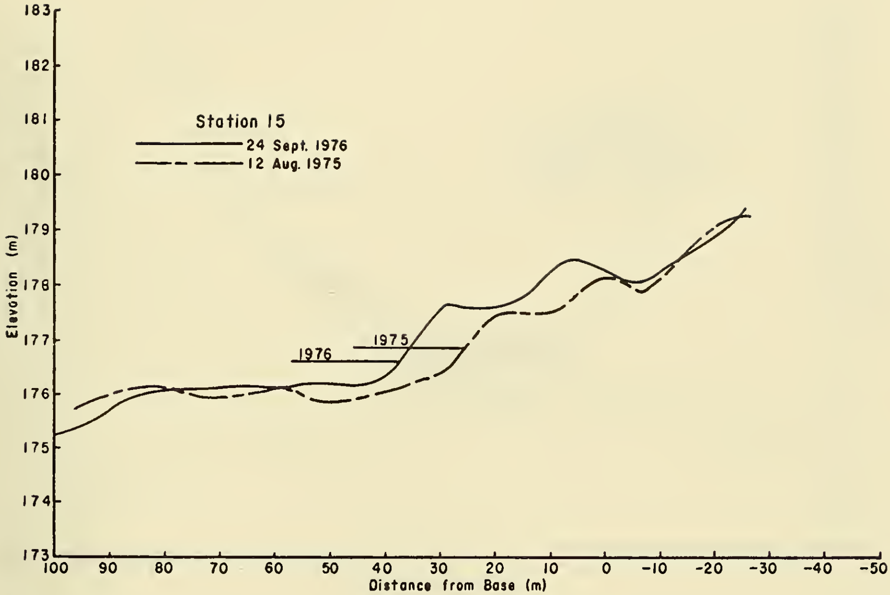

STATION 10
11 Sept. 1976
13 Aug. 1975
7 May 1971
22 July 1969
1975
1971
1976
1969
Elevation (m)
183
182
181
180
179
178
177
176
175
174
173
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

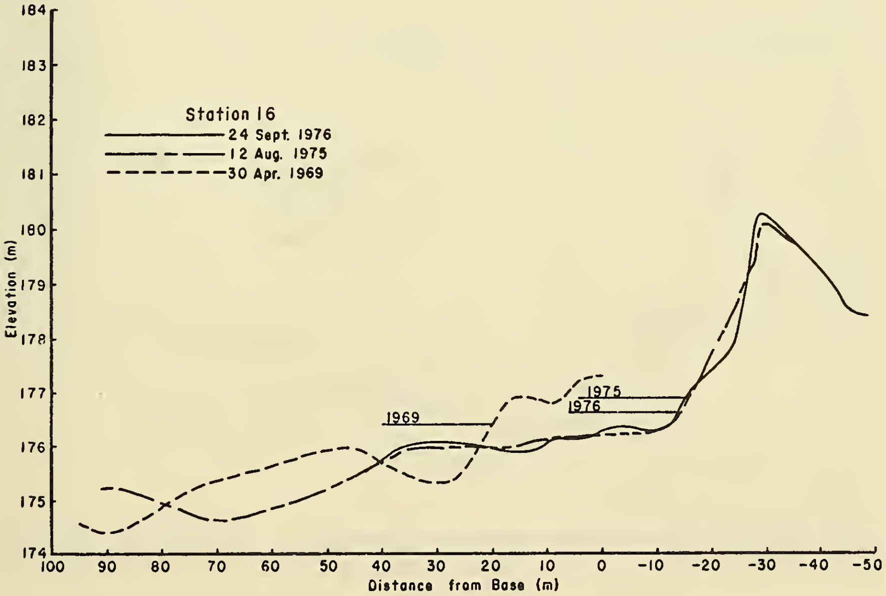

STATION 11
13 Aug. 1975
26 May 1969
23 Oct 1969
Fill
Breakwall
Built in July 1969
1975
1969
1969
Elevation (m)
183
182
181
180
179
178
177
176
175
174
173
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

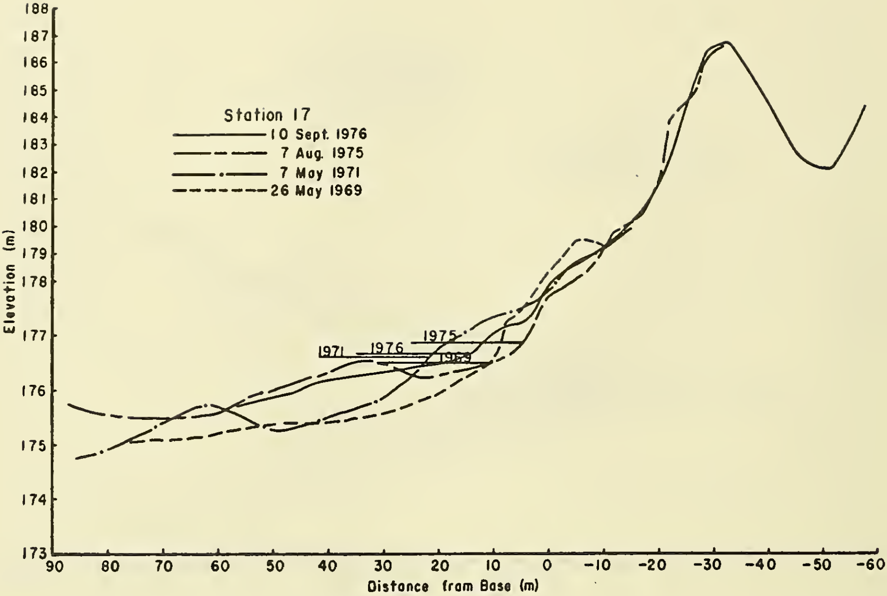

STATION 12
10 Sept. 1976
13 Aug. 1975
30 April 1969
1975
1976
1969
Elevation (m)
183
182
181
180
179
178
177
176
175
174
173
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

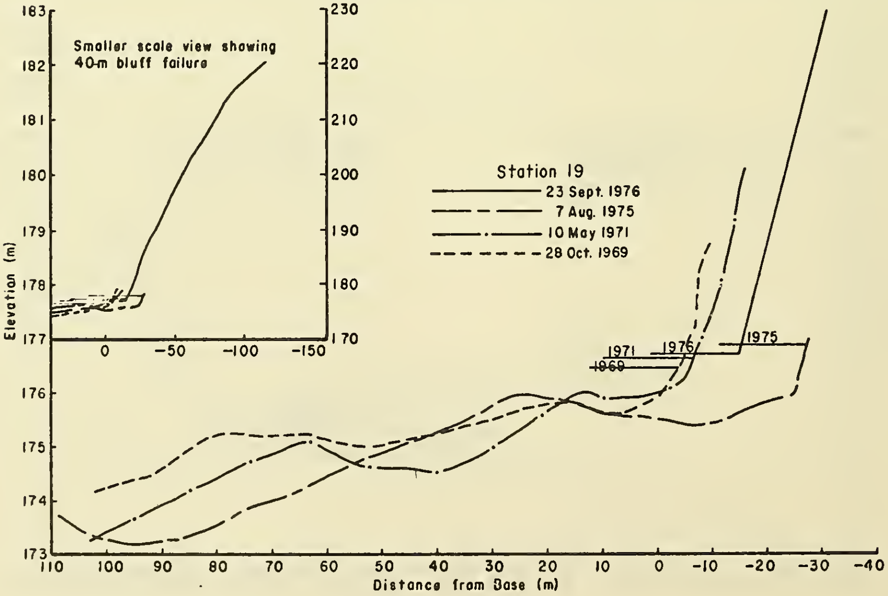

STATION 13
24 Sept. 1976
13 Aug. 1975
13 May 1971
16 May 1969
1975
1976
1971
1969
190
189
188
187
186
185
184
183
182
181
180
179
178
177
176
175
174
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
Distance from Base (m)

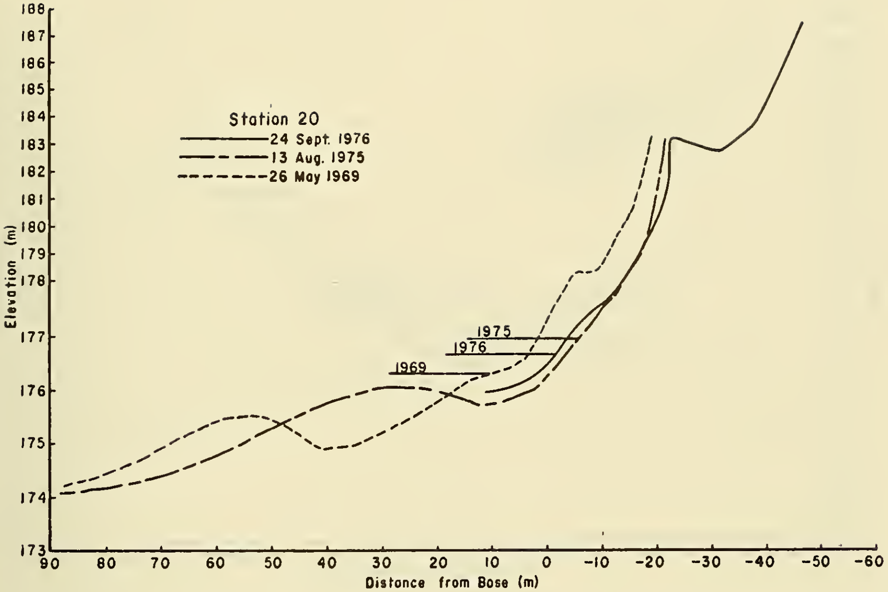

Station 14
24 Sept. 1976
12 Aug. 1975
30 Apr. 1969
1975
1976
1969
188
187
186
185
184
183
182
181
180
179
178
177
176
175
174
173
Elevation (m)
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

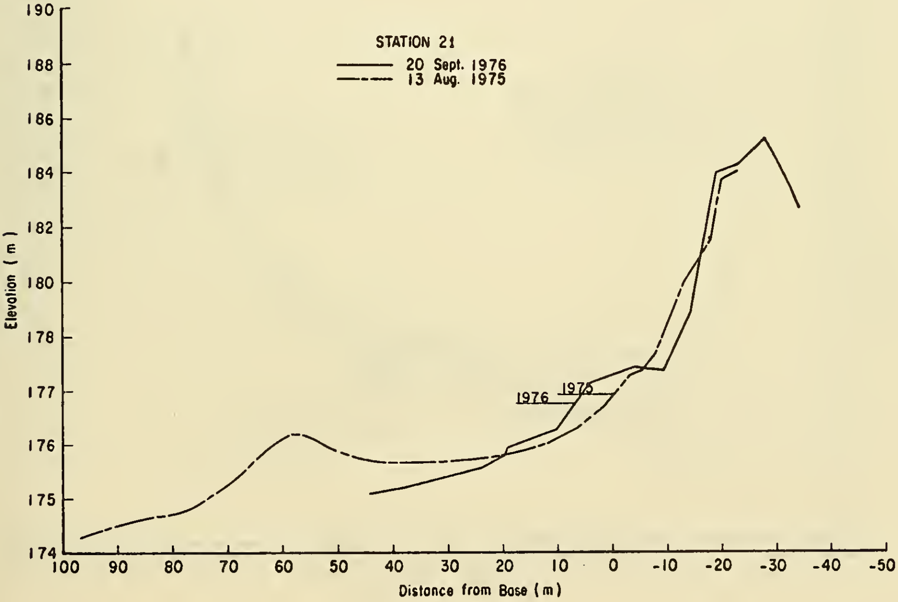

Station 15
24 Sept. 1976
12 Aug. 1975
1975
1976
Elevation (m)
183
182
181
180
179
178
177
176
175
174
173
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

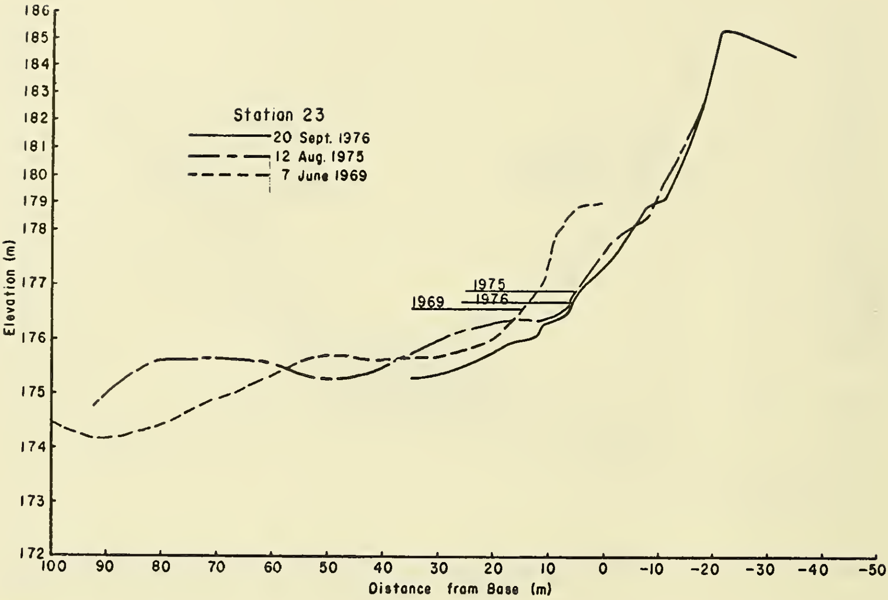

Station 16
24 Sept. 1976
12 Aug. 1975
30 Apr. 1969
1969
1975
1976
Elevation (m)
184
183
182
181
180
179
178
177
176
175
174
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

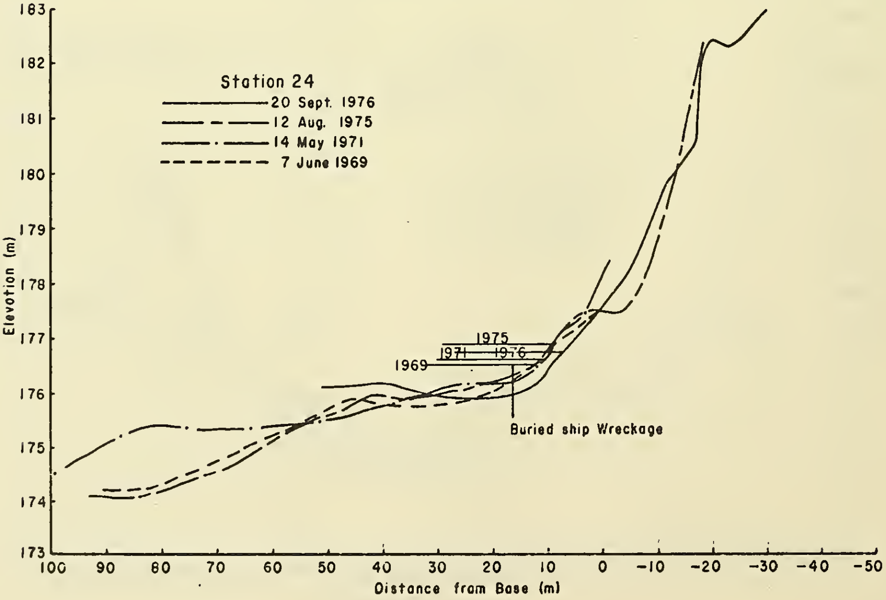

Station 17
10 Sept. 1976
7 Aug. 1975
7 May 1971
26 May 1969
1971
1976
1975
1969
Elevation (m)
188
187
186
185
184
183
182
181
180
179
178
177
176
175
174
173
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
Distance from Base (m)

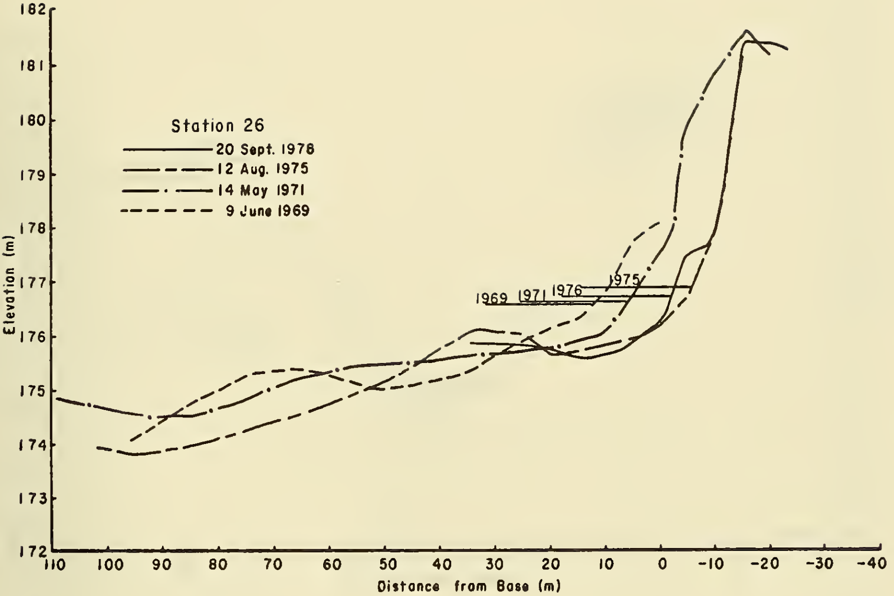

Smaller scale view showing 40-m bluff failure
230
220
210
200
190
180
170
0
-50
-100
-150
Station 19
23 Sept. 1976
7 Aug. 1975
10 May 1971
28 Oct. 1969
1971
1976
1975
1969
Elevation (m)
183
182
181
180
179
178
177
176
175
174
173
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
Distance from Base (m)

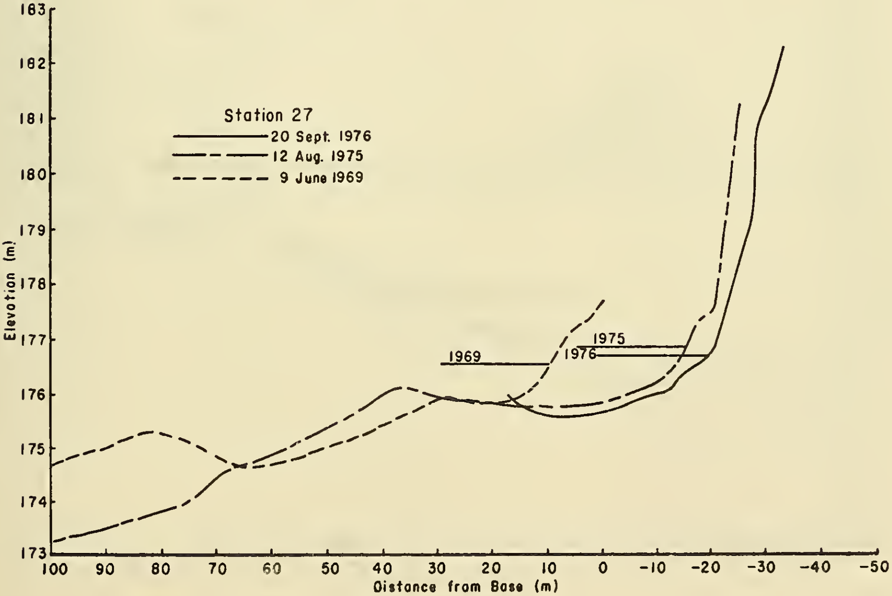

Station 20
24 Sept. 1976
13 Aug. 1975
26 May 1969
1975
1976
1969
Elevation (m)
188
187
186
185
184
183
182
181
180
179
178
177
176
175
174
173
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
Distance from Base (m)

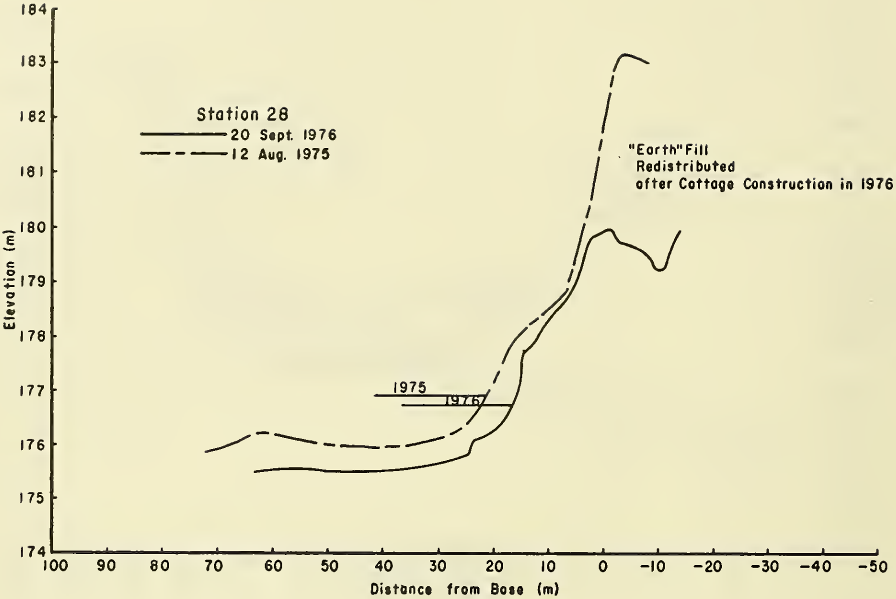

STATION 21
20 Sept. 1976
13 Aug. 1975
1976
1975
Elevation (m)
190
188
186
184
182
180
178
177
176
175
174
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

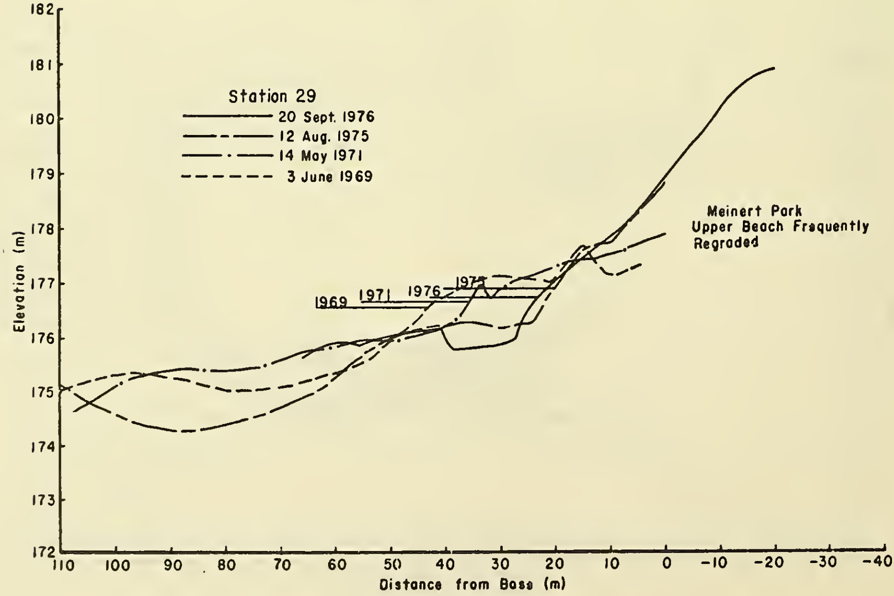

Station 23
20 Sept. 1976
12 Aug. 1975
7 June 1969
1975
1976
1969
Elevation (m)
186
185
184
183
182
181
180
179
178
177
176
175
174
173
172
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

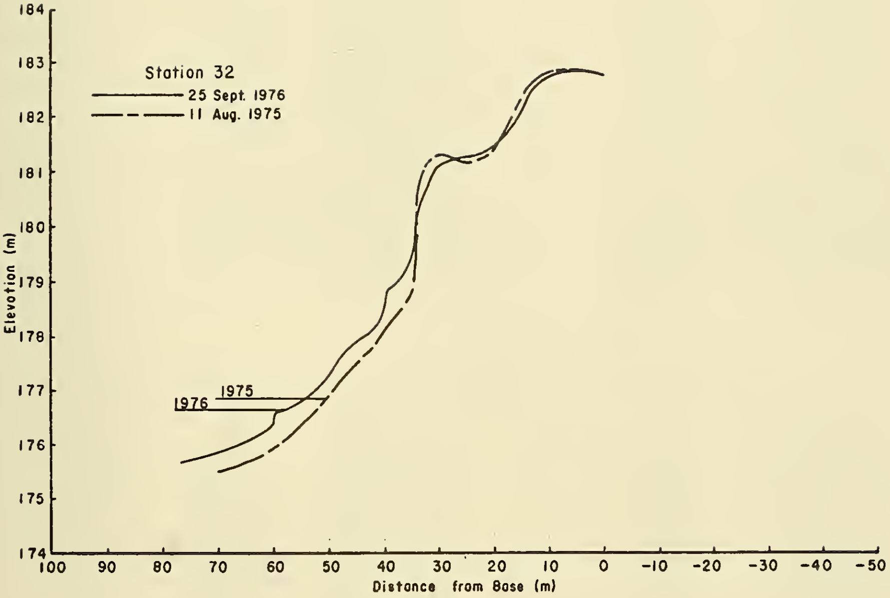

Station 24
20 Sept. 1976
12 Aug. 1975
14 May 1971
7 June 1969
1975
1971
1976
1969
Buried ship Wreckage
Elevation (m)
183
182
181
180
179
178
177
176
175
174
173
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)


Station 26
20 Sept. 1976
12 Aug. 1975
14 May 1971
9 June 1969
Elevation (m)
182
181
180
179
178
177
176
175
174
173
172
1969
1971
1976
1975
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
Distance from Base (m)


Station 27
20 Sept. 1976
12 Aug. 1975
9 June 1969
Elevation (m)
183
182
181
180
179
178
177
176
175
174
173
1969
1975
1976
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)


Station 28
20 Sept. 1976
12 Aug. 1975
"Earth" Fill Redistributed after Cottage Construction in 1976
1975
1976
Elevation (m)
184
183
182
181
180
179
178
177
176
175
174
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)


Station 29
20 Sept. 1976
12 Aug. 1975
14 May 1971
3 June 1969
Meinert Park Upper Beach Frequently Regraded
1969
1971
1976
1975
Elevation (m)
182
181
180
179
178
177
176
175
174
173
172
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
Distance from Base (m)


Station 32
25 Sept. 1976
11 Aug. 1975
1975
1976
Elevation (m)
184
183
182
181
180
179
178
177
176
175
174
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Distance from Base (m)

Hands, Edward B.
Changes in rates of shore retreat, Lake Michigan, 1967-76 / by Edward B. Hands. – Fort Belvoir, Va. : U.S. Coastal Engineering Research Center ; Springfield, Va. : available from National Technical Information Service, 1979.
71 p. : ill. ; 27 cm. – (Technical paper ; no. 79-4)
Cover title.
Bibliography : p. 42.
This report provides information on rates of shoreline recession and on changes in these rates during recent high water levels on the Great Lakes. A graphic summary of field data is presented to estimate effects of future lake level changes in similar coastal environments. Qualitative guidance is provided on how and when these estimates should be adjusted to reflect differences in environmental settings.
1. Beach profile. 2. Beach changes. 3. Lake Michigan. I. Title. II. Series: U.S. Coastal Engineering Research Center. Technical paper no. 79-4.

TC203 .U581tp no. 79-4 627

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