BLUFF EROSION AT SELECTED SITES ALONG THE SOUTHEASTERN SHORE OF LAKE MICHIGAN

VARIATIONS IN WATER LEVEL AND PRECIPITATION IN THE LAKE MICHIGAN BASIN

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AT

SELECTED SITES

ALONG THE

SOUTHEASTERN SHORE

OF

LAKE MICHIGAN

By

William R. Buckler

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ABSTRACT

Based on comparison of the original land survey data of the early 1800's as compared to resurveys in 1956 and 1973 it is apparent that bluff erosion rates are not uniform at selected sites along the southeastern shore of Lake Michigan nor can they be anticipated to be similar at very similar sites during two or more distinct time periods. The factors of bluff composition, height, slope, vegetative cover, beach frontage, hydrological conditions, shoreline orientation and man-made structures in the shore zone were observed at eight study sites in order to determine if any of these variables might be related to erosion rates. Beaches fronting the shoreline bluffs provide the best protection against erosion. Bluff composition, slope and hydrological conditions all are involved in modes of bluff slope retreat. Till bluffs appear to recede through the processes of slumping, block gliding, and fluvial activity whereas sandy bluffs appear to retreat through the process of debris sliding. Major cyclonic disturbances, especially in November and March, in conjunction with high levels provide potentially favorable conditions for bluff erosion. Man-made shore zone structures may cause an escalation in bluff recession instead of preventing shoreline erosion. A case study revealed three severe erosion periods since 1916 in addition to illustrating the dynamic changes possible within a shore zone.

ACKNOWLEDGEMENT

The author wishes to acknowledge appreciation for the instructive guidance of Dr. Harold A. Winters in completing this paper. Appreciation is also extended to Mr. William J. Gibbs, Jr. for his friendly cooperation in making his records and photographs freely available. Special thanks is extended to Mrs. Susan Buckler and Mrs. Claudia Lusch for typing the various manuscripts and Mr. Richard L. Rieck and Mr. David P. Lusch for needed assistance in the survey work.

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INTRODUCTION

The earth's landscape is continuously being modified by natural forces. This fact is especially apparent to many during periods of high water levels on the Great Lakes. Storm systems over the Lakes, especially in fall and spring, generate substantial waves with high energy potential that may vigorously erode the shoreline. Beaches, which are extensive during low water levels and which act as energy absorbers to protect coastal uplands, may be drastically narrowed or even disappear. As a result, waves may be able to reach and erode the landface.

Since 1969 Lake Michigan water levels have been higher than average. The 1972 annual level measured over one foot above the mean while in 1973 the water height has been over 1.5 feet above the average (U. S. Department of Commerce, 1973). This is contrasted to the 1956 to 1968 period when levels were below the long-term mean. For example, in 1964 the lake registered a level 1.82 feet below the norm.

Much of the land adjacent to the Lake Michigan coastline consists of unconsolidated, easily erodible, glacial drift. In many places along the coast are bluffs, 10 to 150 feet in height, which may be experiencing rapid retreat due, in part, to their glacial drift composition.[1]

INVESTIGATIVE OBJECTIVES

The objectives of this study are: (1) to assess rates of bluff retreat at several selected sites along the southeastern shore of Lake Michigan, comparing their present positions with their positions in 1956 and at the time the original land surveys were conducted in the 1830's; (2) to provide information from a case study which reveals three severe erosion periods since 1916; (3) to determine relationships of selected variables to rates of bluff retreat; and (4) to ascertain and describe modes of bluff slope retreat.

PREVIOUS STUDIES

"There is an overall lack of systematic field data on coastal erosion in the Great Lakes as a whole and Lake Michigan in particular" (Davis, 1972, p. 1). This shortcoming is especially acute for the shore zone along the eastern part of the lake. The earliest recorded measurements of erosion along this portion were cited by Leverett (1899, p. 458) for eight points along the shoreline of Berrien County, Michigan. He published results of

[1]This is not to say, however, that all bluffs of glacial drift are experiencing substantial erosion.

measurements made by a surveyor named Galvin which indicated an average annual bluff loss of 3.30 feet during the 41 to 57 years following 1828 (Powers, 1958, p. 87). The Corps of Engineers (U. S. House of Representatives, 1958, p. 17) estimated that the average rate of bluff erosion along the shoreline segment between St. Joseph and the village of Shoreham in Berrien County was 2.1 feet per year prior to 1958.[2]

Recently the Corps of Engineers (U.S. Department of the Army, 1971a) has published a report which included an appraisal as to the erosional problems existing along the eastern shoreline of Lake Michigan. No quantitative measurements, however, were included. More recently Davis (1972) has completed a two year beach profiling project at 17 nearly equally spaced sites along the eastern coast. Erosional rates varied from zero to 25 feet in any one year at a specific location.

> Of all locations, 12 exhibited at least some erosion . . .however, only half of these (6) show some erosion during both years. . . . A wide variety of combinations exist between location, year and amount of erosion. Only two locations . . . experienced approximately the same amount of erosion both years (Davis and Fingleton, 1972, p. 33).

The most extensive study known is that done by Powers (1958). During two field seasons he mapped in detail the geomorphology of the Lake Michigan shoreline. At 134

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[2]It was not indicated how many years "prior" meant.

section-line sites, to include 56 along the eastern shore of the lake, he ascertained rates of bluff retreat by comparing original land survey measurements taken in the early 1800's with his own measurements taken in 1956. In addition, he divided the Lake Michigan shore zone into 609 segments and indicated for each the landform type, the height and slope of the inland landscape, and the width and material composition of the backshore and foreshore.

STUDY LOCATIONS

Eight bluff sites located along the southeastern Lake Michigan shore from west of Montague in Muskegon County, south through Ottawa, Allegan and Van Buren Counties to the village of Shoreham, immediately south of St. Joseph in Berrien County, were selected for this study (Figure 1). Erosional rates had been determined for each of these sites by Powers (1958) in 1956 and conditions allowed for accurate re-survey measurements to again be taken during the course of this study at seven of the eight locations. The shoreline of the sites tends to be gently curved with the northern sector oriented to the north-northwest with a gradational change in direction to the southern part which extends in a southwesterly direction. The landface consists mainly of sand dunes or high and low bluffs composed of till, sand and gravel, silt and clay or an assortment of these sediments.

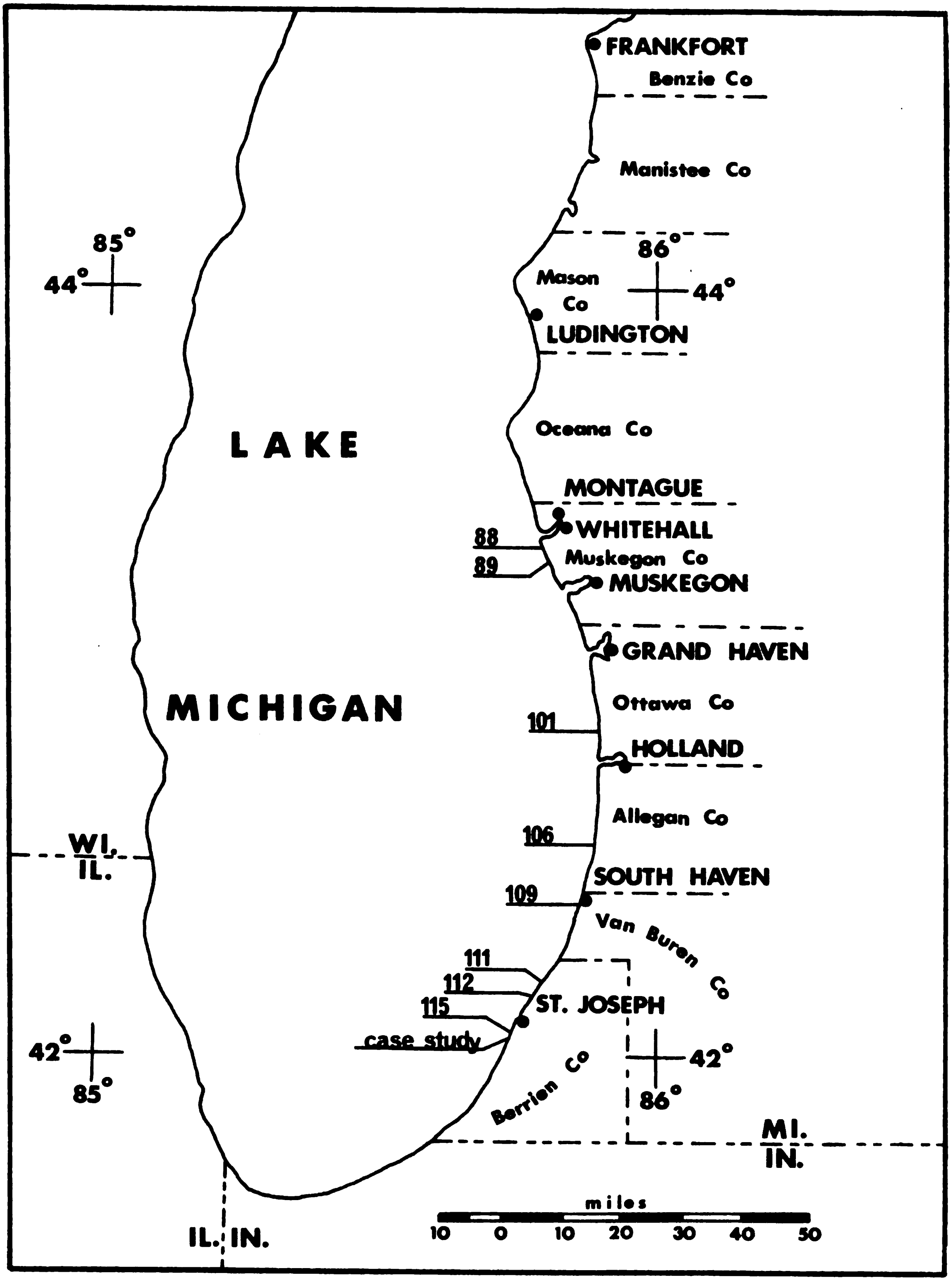

Figure 1: Location of study sites.

These sediments are unconsolidated and are from Pleistocene to Recent in age. No pre-Pleistocene bedrock formations are known to be exposed. The Corps of Engineers (U. S. Department of the Army, 1971a, pp. 86 and 94) has designated approximately 48 percent of this shore segment as areas of critical erosion.

In addition to these eight sites is one associated with a case study to be discussed later. The location of this site is in the village of Shoreham and is adjacent to the most southern of the eight sites mentioned above.

VARIABLES UNDER CONSIDERATION

In addition to obtaining the annual rate of bluff retreat between the 1830's and 1956 and ascertaining the yearly rate of bluff erosion between 1956 and 1973, eight factors were considered in relation to bluff erosion rates at each of the study sites. These variables are: (1) the bluff composition, (2) the bluff height, (3) the bluff slope, (4) the vegetative cover on the bluff slope, (5) any hydrological phenomena within the bluff, (6) the shoreline orientation, (7) the existence or non-existence of beach frontage, and (8) any visible effect of man-made shore zone structures on the bluff.

INVESTIGATIVE PROCEDURES

Following an initial reconnaissance in July, 1973, of 20 section-line sites included in the original study by Powers, eight bluff sites were selected for re-examination and assessment in August, 1973. These eight sites were selected because they provided variations in the factors under consideration, especially those of bluff composition and shoreline orientation. In this study each of the eight locations is given a site number which duplicates that of Powers' station number for that particular locality.

Powers had measured the distance from a section corner, located within one mile of the lake shore, to the upper bluff edge at each of the eight sites. He also obtained from copies of the original U. S. land survey notes of the 1830's the chained distances from these same section corners to the lake's "meander line." Assuming that in most cases the "meander line" represented the bluff line, he was therefore able to calculate an average annual rate of bluff retreat at each of the study sites.

In this study the original government notes were re-examined and the distances between bluff sites and section corners recorded. Extrapolation from Powers' report provided figures as to what these distances were in 1956. On August 7-8, 1973, seven of the eight section-line distances were again chained, thereby enabling yearly erosion rates to be computed between 1973 and both 1956 and the 1830's.[3]

With one exception, all distances in this present study were chained with a 100 foot steel tape. A 300 foot segment along the site 88 transit line was calculated by trigonometric means due to the slope involved.

At each bluff site evidence pertaining to the eight variables under consideration was recorded. At some sites mass-wasted overburden covered part of the in-situ sediments. In these cases the nature of the sediment was determined by examining exposures generally within 30 feet either side of the site line. Calculations from topographic maps were used to determine bluff height at several localities because dense or tall vegetation on the slope precluded accurate trigonometric measurements. In places where pedestrian traffic had notched sags in the bluff's upper edge and had modified the natural slope, measurements as to bluff height and slope angle were taken immediately north or south of the site line.

The water of Lake Michigan generally rises to the highest level in its annual cycle in the latter part of the summer. A change in lake level affects a change in beach width. Since each site was observed in both early July and

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[3]No survey measurement was taken at site 112. The section corner could not be adequately located in the field. In addition, after examining the original land survey notes, the 15-minute, 1927, topographic map and the 7½-minute, 1970, quadrangle, it became obvious that Powers' bluff retreat figure in the 1958 report was substantially in error.

early August, two measurements of the beach width fronting each bluff location were recorded.

SITE DESCRIPTIONS

The eight main study sites vary significantly. Three bluffs (sites 89, 101 and 115) were primarily composed of sand and gravel, three (sites 106, 109 and 111) largely of glacial till, one (site 88) of dune sand, and one (site 112) of assorted glacial drift. Bluff heights ranged from 30 feet (sites 88 and 101) to almost 110 feet (site 112) whereas bluff slopes were generally greater than 30 degrees and at several sites were vertical in at least a portion of their slope. The shoreline trended from N27°W (site 89) through north-south (site 101) to N36°E (site 112). Vegetation, in some degree, existed on the slopes at four sites (89, 106, 111 and 112). Groundwater percolated out from those bluffs (sites 106, 109, 111 and 112) which contained till in some portion of their profile. Beaches fronted four bluffs (sites 89, 106, 111 and 112) during at least one of the visits to each location. Man-made structures were present at the water's edge at four sites (88, 89, 109 and 115). All but three bluffs (sites 89, 106 and 111) presently appeared to be experiencing substantial erosion.

A detailed descriptive account of each bluff site is included as an appendix to this paper.

CASE STUDY

The purpose of this section is to describe how a shoreline may evolve through time at a single bluff location. A series of photographs[4] is included to illustrate the dynamic nature of a shore zone. Much of the information presented in this section has been provided through the courtesy of Mr. William J. Gibbs, Jr., whose coastal property is the subject of this case study. Due to interest and as proof for tax credit, he has kept records as to bluff erosion along his property. These records include certified and personal survey measurements, photographs, newspaper articles and personal observations and notations.

Case study location

The shore zone bluff under consideration is located along the Lake Michigan boundary of the village of Shoreham, immediately south of St. Joseph in Berrien County (Figure 1). The bluff segment is approximately four miles south of the jetties at the entrance of the St. Joseph harbor. Mr. Gibbs' property width extends 240 feet southward from a point 399.5 feet south of the northeast corner of section 9, T5N, R19W.

[4]All photographs with the exception of Figure 2 were provided by Mr. William J. Gibbs, Jr. In no cases were black and white negatives available. Due to this fact and the age of the original photos, the quality of the reprints may not be as good as would be desired. The sequence of nine photos in Figure 8 were copied from color slides. Black and white prints of those were unobtainable.

His property length measures from South Lake Shore Drive westward to the water line.

The bluff along this shoreline segment is composed largely of water-laid fine to medium sand with scattered pebbles. The trend of the shoreline is north 27 degrees east and in the past the bluff line was relatively straight. Presently, however, the bluff line along a 425 yard stretch, to include Gibbs' lot (in addition to site 115 in the main study), is concave inland as a result of accelerated erosion along that portion of the bluff (Figure 2).

Lake Michigan is approximately 70 miles in width at this point. Of winds which generate waves affecting the area, those from the north have the greatest fetch, 225 miles; those from the southwest have a fetch of 50 miles. "During severe storms with a frequency of about once a year, waves may range up to 11 feet in height in deep water, but ordinarily waves of this height break before reaching the shore structure" (U. S. House of Representatives, 1958, p. 4).

Shoreline evolution

Mr. Gibbs has recognized three periods of severe erosion along the bluff since his family purchased the shoreline property in 1916 (Table 1). He reports that at that time abundant vegetation including large trees grew on top of, and on the slope of, the bluff along the entire area from

Figure 2: The present shoreline bluff at the case study location. Note its concave nature where accelerated erosion has taken place.

Table 1: Average* retreat of upper bluff-line along the Lake Michigan shoreline property of William J. Gibbs, Jr. during each of the severe erosion periods since 1916. All measurements were provided by Mr. Gibbs.

EROSION PERIOD	AVERAGE LOSS DURING PERIOD	AVERAGE LOSS PER YEAR
1928 - 1931	19.9'	6.60'
1946 - 1953	55.1'	7.87'
1969 - 1973 (Jul 12)	63.0'	15.75'

* The average is computed by dividing the sum of the bluff retreat figure at the north and south property lines by two.

the St. Joseph harbor south to the southern limit of the Grand Mere area. There included some 75 to 100 foot high white pines along old wagon trails which led down to the beach.

According to Gibbs, little erosion was evident along the shoreline between 1916 and 1928.[5] In the latter year, however, the first of the three most recent severe erosion periods began. From a 1940 certified survey it was estimated that between 1928 and 1931 the bluff had retreated 19.9 feet, for an average of 6.6 feet per year (Tables 1 and 2). A picture taken in the summer of 1937 reveals a good recovery of the beach and bluff (Figure 3).

The bluff was essentially stable from 1931 to 1945 after which time the second period of extensive severe erosion began. Bluff loss totaled 55.1 feet when the erosion period ended in 1953 (Tables 1 and 2). A photo (Figure 4) taken on March 6, 1949, depicts an eroded bluff and according to Mr. Gibbs, by the spring of 1952 no growth of any kind remained on the bluff.

In September, 1948, three 50 foot groins and a 230 foot seawall were constructed because of occurring and

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[5] Gibbs is also convinced after tracing the previous ownership and legal description of his property back to 1872, from his own recollection of the shoreline bluff (and expecially the nature of the vegetation on the slope) as a youngster and after examining old family photos that no serious bluff erosion occurred for many years prior to 1916. He believes that the bluff line was essentially the same in 1872 as it was in 1916. This assertion could not be presently confirmed by the investigator.

Table 2: Recorded measurements along the north and south boundary lines of the William J. Gibbs, Jr. property. The distances are those taken from a hedge 33 feet west of the center of S. Lake Shore Drive to the top of the Lake Michigan bluff. All measurements were provided by Mr. Gibbs.

DATE	SOUTH LINE	LOSS IN FEET		NORTH LINE	LOSS IN FEET		MEAN LOSS IN FEET	
		DURING PERIOD	ACCUMULATED LOSS		DURING PERIOD	ACCUMULATED LOSS	DURING PERIOD	ACCUMULATED LOSS
Oct. 18, 1916	1200.0	----	------	1090.0	----	-------	------	------
to Dec. 5, 1940	1190.2	9.8	9.8	1060.1	29.9	29.9	19.9	19.9
to Oct., 1955	1130.0	60.2	70.0	1010.0	50.1	80.0	55.15	75.0
to June 13, 1967	1130.0	0.0	70.0	1010.0	0.0	80.0	0.0	75.0
to May 3, 1973	1096.0	34.0	104.0	918.0	92.0	172.0	63.0	138.0

<u>AVERAGE LOSS PER YEAR</u>

1916-1973 = 2.42'
1946-1973 = 4.37'
1969-1973 = 15.75'

Figure 3: Good recovery of the beach and bluff after the erosion period of 1928 to 1931. The photo was taken during the summer of 1937.

Figure 4: Bluff badly eroded by the spring of 1949 during the erosion period of 1946 to 1953.

anticipated erosion along the shoreline property during this second erosion period. Sand had been removed from the lake bottom to almost cover these structures. Two years later during a storm, reported by Gibbs to have had a duration of 23 hours with winds up to 70 mph, on November 18-19, 1950, and another major storm a week later on November 25th, the seawall and groins were demolished and the bluff slope devastated (Figures 5 and 6). Mr. Gibbs indicated that by the fall of 1951 the remaining structures appeared to be ineffective and by 1953 they were almost totally gone.

A new era of bluff stability occurred between 1954 and 1968. In 1961 the vegetative growth on the bluff was substantial (Figure 7) and by 1968, as reported by Gibbs, the bluff was covered with many young trees and other growth (Figure 8-B).

Gibbs stated that in the summer of 1968 a large beach fronted, and a heavy growth covered, the slope of the bluff (Figures 8-A and 8-C). This scene changed early in 1969 when the third and present period of severe erosion began. Figure 8 dramatically illustrates the progressive damage done to the bluff in a two year period. A survey on May 3, 1973, revealed that during this latest attack on the bluff, average loss from the top of the bluff had reached an alarming rate of 15.75 feet per year; 63.0 feet had been lost since 1969 (Table 1 and 2).

Figure 5: View of the bluff on December 3, 1950 following the devastating storms of late November.

Figure 6: Demolished seawall and groins, built two years earlier, following the intense storms of late November, 1950. The photo was taken on December 3, 1950.

Figure 7: Reestablishment of vegetation on the bluff slope during the low water stage, 1954 to 1968. This photo was taken on July 4, 1961.

Figures 8-A to 8-I: Sequence of nine photos showing the progressive damage done to the bluff in a two year period as the Lake Michigan level rose during the last erosion period.

Figure 8-A: March, 1968: Shows large beach and heavy growth on bluff; breakwaters are neighbor's next door.

Figure 8-B: March, 1968: Shows dense tree plantings on the bluff before summer foliage is out.

Figure 8-C: October 31, 1968: Shows large beach and heavy bluff growth before storm damage early in 1969.

Figure 8-D: March 27, 1969: Shows severe damage to bluff and loss of trees and path damage from storm of March 25-26, 1969.

Figure 8-E: July 29, 1969: Shows more bluff and tree loss from the storm of July 27-28, 1969.

Figure 8-F: November 22, 1969: Shows the bluff after the storm of November 19-20, 1969.

Figure 8-G: November 22, 1969: Shows view of bluff and beach, looking north after the storm of November 19-20, 1969.

Figure 8-H: December 5, 1969: Looking north showing loss from top of bluff caused by the storm of November 19-20, 1969.

Figure 8-I: December 5, 1969: Same view as photo 8-A; looking south showing bare bluff and loss from top caused by the storm of November 19-20, 1969.

Discussion

Since 1916 Gibbs' Lake Michigan shoreline bluff had become stabilized during each period of low water heights while during high levels loss of bluff material had been considerable. The water level began to rise substantially in 1928, although it still was below the long-term average. The level was above the norm in 1929 and 1930 before dropping again in 1931. During the 1928 to 1931 erosion period bluff recession was three times greater along the northern property line than along the southern one (Table 2). It appears that at the southern extent remnants of several groins and a breakwater, built in 1906, had somewhat reduced the rate of erosion.

The lake rose slightly above the mean in 1943, dipped below normal between 1948 and 1950 before rising above average during the years 1951 to 1955. The severe erosion occurring during November, 1950, can be at least partially explained by the fact that it was associated with a storm with wind gusts up to 70 mph and a duration of 23 hours.

The Lake Michigan level rose above the statistical norm again in 1969, the same year severe erosion began once more on the bluff. High lake levels and extensive bluff retreat are continuing today.

During the present erosion period the northern bluff crest has been eroded almost three times as fast as that at the southern limit. This situation appears to be attributed to the position of the remains of a breakwater, built in 1952, adjacent to and south of Mr. Gibbs' property. Located a short distance offshore, it prevents the full impact of the waves from reaching the landface. This decaying structure was supplemented by a concrete seawall constructed along this same shore section last year. Similar structures do not exist along or near the northern margin of the shoreline property.

Several questions relating to the shoreline description and erosion are not as easily answered. What factor(s) has caused the present bluff line to be curved inward along a 425 yard stretch while in the past it had been relatively straight? Why has the annual average bluff erosion rate been progressively higher during each of the three erosion periods? If it is assumed that Gibbs was correct, why was there apparently no serious erosion on the bluff between 1872 and 1916?[6]

Evidence is lacking but the jetties at the entrance of the St. Joseph harbor may very well have been and are important factors in the shoreline evolution in a downdrift direction which would include the vicinity of the case study site. It is cautiously suggested that they may be related to the answers to the questions raised above.

In 1836 the first 1,023 feet of the north pier at St. Joseph was built, this being the first lake structure constructed in the area. By 1880 another 804 feet had been

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[6]The reader is advised that this conclusion has not been verified in this study.

added, this segment on a new alignment, thus forming an angle point in the pier. By 1903 the remaining 1,002 feet of the 2,829 foot north pier had been built in addition to the construction of a south pier (U. S. House of Representatives, 1958, p. 18).

Examination of the 1927 topographic map reveals a substantial build-up of sand behind and north of the jetties. This accumulation extends further lakeward than the angle bend in the north pier, thus implying that a sand beach at least 1,023 feet in width had formed immediately adjacent to the pier since it was first constructed. More recent aerial photographs and the 1970 topographic map reveal that the sand extends approximately 150 feet further waterward than the angle bend.

Prior to the construction of the north pier the mouth of the St. Joseph River had turned to the south (U. S. House of Representatives, 1958, p. 18). This deflection suggests that dominant movement of significant amounts of sediment is southward along this part of the shoreline. Thus it appears that the construction of the piers disrupted the natural littoral transport of beach building material to the south of the harbor entrance and changed the regimen of the beach zone. The Corps of Engineers confirms these conclusions (U. S. House of Representatives, 1958, pp. 4 and 22).

> Although a beach may temporarily be eroded by storm waves and later restored by swells, and erosion and accretion

> pattern may occur seasonally, the long-range condition of the beach - whether eroding, stable or accreting - depends on the rates of supply and loss of littoral material. Erosion or recession of the shore occurs when the rate of loss exceeds the rate of supply (U. S. Department of the Army, 1971b, pp. 21-23).

Furthermore, the Corps of Engineers (U. S. House of Representatives, 1958, p. 23) state that

> groin construction alone is not a suitable means of stabilizing the bluff in the portion of Berrien County immediately south of St. Joseph Harbor, as natural sources of supply are insufficient to supply material at a rate required for impounding a suitable protective beach.

The foregoing statements seem to lead to a possible conclusion that ever since the construction of the jetties at the St. Joseph harbor entrance a naturally occurring protective beach is no longer able to maintain itself to the south. Once the original beach was carried away through wave action, and with no possibility for re-nourishment, accelerated erosion of the backing bluffs was inevitable, especially during substantial storms and periods of high lake level.

Conclusion

Several relationships have been illustrated by this case study. Unconsolidated glacial drift is easily susceptible to erosion by waves. Bluff erosion is much more likely during periods of high lake levels than during low water periods when slopes tend to become stable. Storms can have drastic consequences on the landface, even during times of low lake level. Man-made structures may possibly either reduce or accelerate bluff erosion but no structure seems to fully prevent it.

BLUFF RETREAT - RATES, FACTORS AND MODES

Comparison of average annual bluff erosion rates prior to, and since, 1956

On the basis of the current investigation and Powers' study (1958) a comparison can be made of bluff erosion rates between the period of the 1830's to 1956 and the period 1957 to 1973 at seven[7] of the eight study sites (Table 3). Average annual erosion rates were not always similar for the two periods under consideration at a given site (Table 4).

Sites which recently experienced insignificant amounts of bluff erosion

The crest-line at bluff sites 89, 106 and 111 experienced no or an insignificant amount of retreat between 1956 and 1973 (Tables 3 and 4). In contrast, the calculated annual rate of bluff erosion between the 1830's and 1956 at these locations revealed losses averaging from 1.03 to ~~1.41~~ 3.09 (correction) feet per year (Table 4).

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[7] Bluff retreat figures were not established at site 112.

Table 3: Locations of study sites and their total bluff-line retreat since the original U.S. land surveys were completed.

SITE NO.	COUNTY	LOCATION	ORIGINAL SURVEY DATE	DISTANCE TO "MEANDER LINE"	BLUFF RETREAT TO 1956	BLUFF RETREAT 1956-1973	TOTAL BLUFF RETREAT TO 1973
88	Muskegon	NW cor/sec 23/T12N,R18W	1837	3,098.7 '	128'	~~0.0~~ 36.9'	~~128.0~~ 164.9'
89	Muskegon	NE cor/sec 31/T11N,R17W	1837	4,488.0 '	169'	0.0 '	169.0 '
101	Ottawa	S¼ post/sec 16/T5N,R16W	1832	924.0 '	66'	9.0 '	75.0 '
106	Allegan	N¼ post/sec 30/T2N,R16W	1831	1,051.38'	130'	2.88'	132.88'
109	Van Buren	NW cor/sec 15/T1S,R17W	1837	995.94'	348'	40.44'	388.44'
111	Berrien	SE cor/sec 21/T3S,R18W	1830	4,290.0 '	390'	0.0 '	390.0 '
112	Berrien	SE cor/sec 3/T3S,R18W	1830	1,914.0 '	-----	-------	--------
115	Berrien	SW cor/sec 3/T5S,R19W	1829	957.0 '	142'	81.0 '	223.0 '

corrected WRB

Table 4: Description of study site variables.

SITE NUMBER	MEAN ANNUAL BLUFF RETREAT TO 1956	MEAN ANNUAL BLUFF RETREAT 1956-1973	BLUFF COMPOSITION	BLUFF HEIGHT	BLUFF SLOPE (in degrees)	SHORELINE ORIENTATION (in degrees)
88	1.07'	2.17'	Dune Sand	30'	31½-37	N14W
89	1.41'	0.00'	Med. Sand With Scattered Pebbles	45'	30-37	N27W
101	.53'	.53'	2-3' Eolian Sand 26' Med.-Cr. Sand	30'	30-34	N-S
106	1.03'	.17'	5' Sand & Gravel 26' Till	55'	35-49	N6E
109	2.74'	2.38'	5½' Sand 1' Sand & Gravel 34' Till	41'	Top 14' 90 Remain. 35-40	To N N13E To S S28W
111	3.08'	0.00'	6-7' Sand & Gr. 60-62' Till 2-3' Sand Nip	70'	Sa. & Gr. 55-90 Till 30-45	N35E
112	-----	-----	12-15' Till 85-98' Various Beds of Sa., Sa. & Gr., Silt & Clay	100' to 110'	30-90	N36E
115	1.11'	4.76'	Water-Laid Sands With Scattered Small Pebbles	60'	Top 3' 90 Remain. 30-35	N27E

Table 4: continued

VEGETATION	HYDROLOGICAL FACTORS	BEACH	"PROTECTIVE" STRUCTURES	PRESENT CONDITION	SITE NUMBER
None	None	None	Breakwater to North Groins to North & South	Severe Erosion	88
Grasses Bushes Young Trees	None	July 10' Aug. 4'	Groins	Stable 2' Nip in Base of Slope	89
None	None	None	None	Severe Erosion	101
Grasses Small Trees	Ground Water Seepage	July 10' Aug. None	None	Rel. Stable 3' Nip 3-5' Exp. Near Top Where Slumped	106
None	Ground Water Seepage Drain Pipe	None	Concrete Slabs Adj. & South Jetties One Mile North	Severe Erosion	109
Wooded	Ground Water Seepage	July 39' Aug. 25'	None	Rel. Stable Minor Slump Near Top, None At Base	112
Sparse to None	Ground Water Seepage Drain Pipe	July & Aug. 20-25'	None	Unstable Slumping Gullying 10' Nip At Base	112
None	None	None	Breakwater - Groin Complex Adj. & South Jetties Four Miles North	Severe Erosion	115

The bluff at site 89 is composed predominantly of water-laid sand whereas at sites 106 and 111 exposures reveal till. Remnants of a low foredune, probably developed during low water stage, fronted the bluff at site 111. All three slopes had an abundant cover of vegetation with the most dense growth at site 111. Furthermore, these three bluffs were the only ones which had been fronted by a beach during at least one of the visits to the sites[8] during the summer of 1973.

Man-made shore zone structures (in this case, permeable groins) exist only at site 89. One-hundred and forty yards south of this site erosion has been quite severe in a segment of the sand and gravel bluff immediately adjacent and north of an impermeable groin.

Slumping and block gliding of undetermined age have occurred on the slope of both till sites (106 and 111). At each of these locations sandy beds overlie the till. Groundwater was observed seeping out from the bluff slope at the base of this sandy layer at both locations.

Sites which recently experienced accelerated erosion rates

The sand dune bluff at site 88 has eroded back at an average annual rate twice as fast (2.17 feet per year average) as it did prior to 1956 whereas the rate at site 115 is four

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[8]This does not include site 112 for which no rates of retreat were determined.

times greater (4.76 feet per year average) than before 1956. The bluff at this latter site consists largely of water deposited sand. Both bluff slopes are presently free of vegetation and each is currently experiencing severe erosion.

Breakwaters and groins, constructed within the last three years, are adjacent to the resurveyed section line at both sites and site 115 is located approximately four miles south of the jetties at the St. Joseph harbor entrance. (For a detailed discussion relating to these jetties see page 28).

Sites which recently experienced erosion
rates similar to those prior to 1956

Two bluff segments (sites 101 and 109) are presently retreating at average annual rates similar to those which they were experiencing prior to 1956. ~~Both bluffs are~~ The predominately till bluff at site 109 is currently retreating at a rate five times greater (2.38 feet per year average) than that of the sand bluff at site 101. (Table 4). Each of their bluff slopes is presently void of vegetation.

Protective barriers do not exist in the area adjacent to the base of the sand bluff (site 101). However, at the till bluff (site 109) concrete slabs have been placed at the base of the slope immediately south of the site. The slope behind these slabs is partially covered by clumps of grasses and is less steep than at the site line.

At site 109 groundwater may seep out from the bluff face at the base of the permeable sand and gravel layer which overlies the till and the mid-slope is covered by a mixture of till and sand and gravel which has slid down from further upslope. No groundwater percolation is visible at site 101.

The bluff at site 109 is situated one mile south of the South Haven harbor. From a point one-third of a mile south of this survey point the shoreline to the north curves noticeably inland all the way to the harbor jetties. Erosion along this stretch is severe (U.S. Department of the Army, 1971a, p. 86).

A major area of sand dunes exists along the shoreline three miles north of site 101. Examination of the topographic map and air photos suggest that the dominant littoral drift is mainly to the south along here. No major structures extend into the lake between the dunal area and the bluff at site 101, which since 1832, has been retreating at an average annual rate of .53 feet per year.

Selected variables investigated in relation to bluff erosion rates

At each bluff site eight variables[9] were observed to determine if they might have a clear relationship to recent erosion rates. Only two factors appeared to have a definite relationship to rates of bluff recession and a third factor

[9](1) Bluff composition, (2) bluff height, (3) bluff slope, (4) vegetative cover, (5) hydrological phenomena, (6) shoreline orientation, (7) beach frontage, and (8) man-made structures.

may be related in a meaningful way. Three variables, although not related to actual rates of erosion, were related to modes of bluff retreat. Two other factors revealed no apparent relationship to rates of erosion.

Beach frontage and vegetative cover

"A wide beach is the best protection the upland shore can have from wave attack" (U.S. Department of the Army, 1971a, p. 13). It acts as an energy absorber as incoming waves over-steepen and collapse along the shoreline. During periods of above average lake levels, however, beaches may become narrowed or submerged. In these cases wave action may then more easily reach the base of, and become quite destructive on, the slope of the landface.

The preceding relationships were reaffirmed during this investigation. The three bluff sites (89, 106 and 111) which had insignificant rates of bluff retreat since 1956 had been fronted by a beach during either or both July and August of 1973 (Table 4). (Beaches existed at no other sites which were resurveyed and at all of these sites the bluffs had experienced recent erosion and their slopes were presently void of all vegetation.)

Even though waves have eroded a two-to-three foot nip in the sand (site 89), till (site 106) or low foredune (site 111) at the base of the bluffs, an extensive cover of vegetation exists on the slope. However, in the cases of sites 89 and 106, an especially critical stage seems to have been reached. It appears that if the water level should remain high above average for an extended period, erosion and removal of vegetation by storm waves at the base of these bluffs could become severe. This situation is possible, but not quite as likely, at site 111 for two reasons. Here the beach is still relatively wide (25 feet) and the bluff itself is fronted by the remnants of a low foredune.

Foredunes may act as effective secondary defenses should beaches become diminished. It is apparent that they act much like breakwaters in preventing wave attack along the base of the bluffs. Exactly what accounts for their formation is not known but investigation into this matter could be promising. If the mechanics and nature of their formation could be determined it may become possible to artificially induce them to form along the shoreline at times of low or average water levels. This in turn may help reduce or prevent bluff retreat during times of high water.

Shore zone man-made structures

The construction of man-made structures along the Lake Michigan shore zone has increased in number since 1956, yet limited evidence indicates that they may be of little or no help at given locations (Table 4). In fact, in the case of groins and jetties, they may accelerate erosion, if not at their own sites, at adjacent localities and especially in the average downdrift direction.

Brunn (1968, p. 69) states:

> It is not a matter of coincidence that most beach erosion in Florida occurs where the most concentrated development along the shores has taken place. Man's interference with natural shore processes is the major cause of the increased erosion in some of the highly populated areas on the lower East Coast and the lower Gulf Coast of Florida. Groins have caused severe leeside erosion problems in many areas along the Florida shore, and have, unfortunately, often done more harm than good, although this conclusion shall not be generalized. In numerous cases, seawalls have protected valuable property or dune faces, but when built as vertical bulkheads, they have, in fully as many cases, caused a lowering and increased erosion of the beach itself, giving rise to heavy water turbulance by waves colliding with the wall at high tides.

Various types of structures have been built in the vicinity at four of the five locations (to include the case study site) which are presently undergoing substantial erosion (Tables 1, 2 and 4). As previously mentioned, there is reason to believe that current erosion at sites 109 and 115, in addition to at the case study location, is possibly related to jetties projecting into the lake at several harbor entrances. Breakwaters and groins built within the last three years at sites 88 and 115 and at the case study site are not preventing erosion from occuring on the bluff. One-hundred and forty yards south of site 89 two impermeable wooden groins, 25 yards apart, extend 50 feet into the lake. No beach zone exists and bluff erosion is severe for about 40 yards to the north of the northern groin. This erosion appears to be precipitated by refraction of incoming waves off of the groin and into the bluff. Between the two groins a beach approximately 25 feet wide, is elevated two to three feet above the base of the eroded bluff at the north.

There is a real need to evaluate exactly what effect these so-called protective structures are having on shoreline evolution and bluff erosion along the western shore of Michigan. It may very well be that the shore zone acts much like a river system. River systems seek a state of dynamic equilibrium. If any portion of the system is disturbed or changed in some way, adjustment must occur in other portions of the river system. This principle of teleconnection may apply in the case of shoreline structures. For instance, the construction of a groin or jetty at one location along the shore zone may disrupt or change the entire regime along another segment of the coastline because of its ability to prevent or reduce littoral drift and to affect localized currents.

Bluff height and shoreline orientation

The variables of shoreline orientation and bluff height appeared to have no bearing on rates of bluff recession nor do they contribute directly to processes of slope retreat, at least at the locations in this study (Table 4). It seems that even though bluffs of increasing heights provide increased volumes of sediments, waves are nevertheless able to effectively remove the material resulting in a situation where average bluff recession rates appear not to be related to bluff heights.

Bluff composition, slope and hydrological phenomena

Results were inconclusive in an attempt to relate recession rates with bluff composition, slope and hydrological conditions (Table 4). Nevertheless, these three variables appear to perform critical roles in the varying processes of bluff slope retreat. Therefore, discussion of these factors is deferred until modes of slope retreat are treated.

Modes of bluff slope retreat

The bluffs at the nine locations[10] studied were undergoing different modes of recession. Variations depended largely on bluff composition, slope, hydrological situations and vegetation. Sandy (to include sand and gravel) bluffs tend to retreat primarily by the process of debris sliding,[11]

[10] The eight sites and the case study location.

[11] Debris sliding: the rapid rolling or sliding of unconsolidated earth debris without backward rotation of the mass; these slides are characterized by the tendency of the slide material to behave as a more or less cohesionless mass, suffering considerable distortion during movement. They generally occur on fairly steep slopes, typically between about 15 and 40 degrees, and are frequently fairly rapid. The depth of the movement and the degree of distortion involved is influenced largely by the cohesion of the slide debris. At one extreme, heavily weathered clay debris may approach the nature of a "slab slide;" at the other is the "sand run" in slopes of dry cohesionless material, in which the movement involves only the grains in a thin surface layer (Hutchinson, 1968, p. 691).

till slopes by the processes of slumping,[12] block gliding[13] and fluvial activity, and bluffs of assorted glacial drift by a mixture of the aforementioned processes.

Retreat of sandy bluffs

Disregarding for present the factor of vegetative cover, sediment movement on sandy bluffs tends to be frequent and the slopes less steep and more uniform than on till bluffs. Except at the top of the profile where there is usually a

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[12]Slumping (rotational slip): downward slipping of one or several units of rock debris usually with a backward rotation with respect to the slope over which movement takes place. They occur principally in slopes largely formed of, or underlain by, a fairly thick and relatively homogeneous deposit of clay or shale. Failure takes place, usually fairly rapidly, by shearing on a well-defined, somewhat curved, slip surface. This, being concave upward, imparts a degree of backward rotation to the slipping mass which produces sinking at the rear, heaving at the base and back-tilting of the slipped strata. Elongated pools commonly collect in the depression formed behind the slipped mass (Hutchinson, 1968, p. 695).

[13]Block glides: a type of slide in which the moving material moves out or downward without the backward tilting characteristic of a slump (Selby, 1970, p. 32). A block glide is one type of a translational slide. Landslides of this type are usually fairly rapid and involve shear failure on a fairly plane surface running roughly parallel to the general slope of the ground. These slides are widespread in cohesive soils in which the failure surface is predetermined by a marked heterogeneity, such as a sharp transition from soft to hard material with depth, or the presence of an adversely located weak layer within the slope (Hutchinson, 1968, p. 690).

near vertical section three to six feet thick,[14] the sediments tend to settle at their angle of repose (approximately 32 degrees) although in actuality the slopes may vary from 30 to 37 degrees depending on the cementation properties and cohesiveness within individual sand layers. Movement downslope is by individual grain particles. Any slope disturbance tends to result in a downward adjustment of material on the slope. These adjustments result mainly from waves that attack and remove material at the bluff's base, resulting in debris slides of varying magnitude and duration.

It is obvious that vegetation on sandy slopes does not prevent erosion through wave action at the base of the bluff, but it does help to prevent mass-wasting on the slope itself. However, during storms waves may erode and wash away flora rooted in the unconsolidated material at the base of the slope. Under repeated wave action the lower portion of the bluff may erode back and the slope become over-steepened, thus inducing debris slides further upslope. Through this process additional vegetation cover may be removed. Eventually the entire slope may become bare of vegetation and thus even more susceptible to accelerated mass-wasting.

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[14]The reasons that the slopes are near vertical at the upper edge of the sandy bluffs was not investigated in detail in this study but contributing factors may involve rooting of vegetation on the top of the bluff and an upper clay-silt enrichment zone.

Erosion of till bluffs

Bluff slopes in till are generally steeper and vary in form to a greater extent than those developed on sandy bluffs. Slopes are inclined from 30 degrees to near vertical (Table 4) irrespective of position on the slope face. Mass-wasting on the till slopes is discontinuous in time and distance and when it does occur, is mainly by downward movement of blocks of till rather than by way of individual clastic particles.

In order to understand the nature of slope retreat on the till bluffs investigated it may be worthwhile to review several attributes of clay, soil cohesion, porewater pressure and landslides.

Clay is an important constituent of the tills exposed at the study sites. The fine texture of clays accounts for their ability to be both highly porous and highly impermeable. High porosity accounts for their high water holding capacity but their microscopic pores impede an effective flow of water through the clays.

> The cohesion of particles depends largely upon the water between them... In unsaturated soils attractive forces between soil particles exist because of the capillary tension of adsorbed water. The actual strength of the capillary tension is proportional to the radius of the curvature of the water surface between the soil particles. The smaller the radius the greater the capillary tension and hence the more cohesive the soil. Hence,...high moisture contents ...contribute to low cohesion. In a saturated soil surface tension is completely eliminated (Selby, 1970, pp. 36-38).

If water enters a soil it tends to fill up the intergranular spaces causing a rise in porewater pressure, and because of the loss of cohesion of the solid particles, their weight also may be supported by the porewater. If the porewater pressure becomes great (for instance, as water enters the soil from a rainfall) overlying soil and water may "float" on the porewater beneath and the porewater may burst out of the voids. This may cause the soil to move (Selby, 1970, p. 41).

Slumping and block gliding are types of landslides.

> The condition of movement of any particular landslide can be extremely complex. Simply stated, however, a slide is a shear failure which will be set in motion when the stress along the potential surface of rupture exceeds the resistence to shear along that surface. This unbalanced condition may be brought about by (a) an increase in the weight of the overlying material due to the absorption of water; (b) a decrease in the resisting mass due, for example, to undercutting a slope; (c) a decrease in shear strength of the material itself, which may be caused by the absorption of moisture (Leopold, Wolman and Miller 1964, p. 340).

All till bluff sites revealed evidence of slumping or block gliding on the slope, although it may not have occurred within the last several years. At each of these sites evidence of groundwater percolation was noticed on the slope face. At several sites portions of the clay till appeared saturated with water. Since the role of water in the reduction of shearing strength is a major one (Savage, 1968, p. 697) and since clay and silt naturally have low bearing strengths (Savage, 1968, p. 697), it appears that the moisture content within a bluff plays an important role in bluff recession.

The base of a till bluff may be eroded back to a certain threshold without causing downward movement of till blocks from upslope. The critical situation, at which time movement does take place, may occur once the slope attains a critical angle and the groundwater, reinforced by excessive rainwater, fully saturates a portion of the till profile, thereby adding mass, eliminating particle surface tension (cohesiveness), and inducing high porewater pressure within the clayey till.

Since clay and silt are important constituents of most tills, the tills tend to be rather impervious to a very effective downward movement of water. Any channelization of the water, which in effect increases the water's potential erosional power, may initiate extensive gullying into the bluff slope. Site 112 illustrates a bluff segment which has, and is, undergoing severe gullying. In at least a portion of the bluff two drain pipes protrude from the slope face near the crest line. Water flowing from these pipes has carved gullies downslope into the in-situ till section or the thick slumped or glided till blocks covering the bluff face.

Since till is able to stand at angles up to 90 degrees, and since slump or glide blocks frequently do not travel extended distances downslope, the profile of a till slope may change over a period of time. This may occur without any corresponding change in the position of the crest line; or, the top edge of the bluff may recede very slowly or not at all while the base of the bluff may recede rather rapidly, at least until some critical stage is reached. At most till bluff study sites it appeared that slump or glide blocks of several ages were associated with the slope.

Erosion of bluffs of assorted
glacial drift

In many cases along the southeastern Lake Michigan shoreline groundwater seepage appears detrimental to the maintenance of bluff slope but in one case such water may aid in the prevention of accelerated erosion. This situation may take place if a sandy material comprises the lower portion of a bluff whereas the upper part consists of two layers of impermeable material (till and clay, for instance) separated by a permeable sandy sediment. Groundwater may then migrate along this upper permeable sediment bed, saturating the top portion of the impermeable clay layer below while at the same time continuing to remove small quantities of the sand above as it seeps out from the slope face. Eventually support for the till will fail causing the till to slump or glide downward. If the till block is large enough it may cover the sandy portion of the slope below, thus acting as a protective cover against the frequent mass-wasting and removal of the sandy material at the base of the bluff. A situation such as this exists at site 112.

Much the same condition could exist if a bluff of sand and gravel, overlain by till, was eroded by waves at its base. Initially sand and gravel would be removed with the subsequent collapse of the till over the sand and gravel.

Erosion potential as related to storms, time of year, and high water levels

High water levels in themselves do not necessarily result in eroded shoreline bluffs. However, in combination with storms, they may act as highly efficient transport mediums allowing incoming waves to reach the landface. Cyclonic disturbances occur in association with, and are steered by, upper atmospheric wind flow in the middle latitudes. Major disturbances appear to be more common during the transitional seasons and are especially frequent in November and March. During these seasons baroclinity[15] in the westerlies is frequently enhanced, resulting in stronger cyclonic development. More frequent winds with greater speed induce larger waves over the Lake Michigan fetch and when these over-steepen and collapse along the shoreline they may possess great erosional ability. In terms of volume, during most years, it appears that relatively little material is lost during the high or low sun periods.

[15]Baroclinity refers to the meridional pressure gradient.

CONCLUSION

Current rates of bluff retreat were determined at seven of eight study sites along the southeastern shore of Lake Michigan. These rates were compared to those calculated at the same sites for the period from the time of the land surveys of the 1830's to 1956. Bluff erosion rates are not uniform along the shoreline nor can recession rates be predicted to be similar at very similar sites during two or more distinct time periods. Severe erosion is most likely during major cyclonic disturbances. High water levels, although not necessarily a prerequisite for erosion, provide a situation for incoming waves which especially favors erosion of the shoreline bluffs. Of eight variables only that of beach width appeared related clearly to erosional rates. Bluffs fronted by beaches retained vegetation on their slopes because the beaches prevented waves from reaching and disrupting the environment necessary for plant growth. Two factors, bluff height and shoreline orientation, were seemingly unrelated to rates of bluff recession. Investigation as to the effect on shore zone erosion as related to man-made structures ended in inconclusive results. It is believed, although no clear proof is available, that these structures do indeed affect shore zone processes, and therefore, shoreline evolution and erosion. The remaining variables, bluff composition, slope and hydrological condition, all were involved in modes of bluff slope retreat.

It appears that better success in understanding the causal factors in shoreline erosion may be met by extending the investigation into the waters along the shore. Physical limnoligical studies may be more productive than geomorphic studies. Such factors as localized eddies and currents, off-shore bars and littoral drift may prove to be primary factors in the dynamic production of shoreline evolution. In addition, an urgent need seems to exist in determining exactly what effect do man-made structures have on the natural processes which act within the Lake Michigan shore zone.

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APPENDIX

APPENDIX

Site Descriptions

The description of each of the study sites follows the outline listed below. A more detailed description may be obtained from the author upon request.

1. Location
   a) County
   b) Topographic map, series, date of issue
   c) Township and range of the point where the survey measurement begins

2. a) Date of original land survey
   b) Distance from the section corner to the "meander line" at the time of the original survey
   c) Bluff recession between the date of the original survey and 1956
   d) Average annual rate of bluff retreat between 1956 and the year of the original survey

3. a) Distance measured from the section corner to the top edge of the bluff in 1973
   b) Total bluff retreat between 1956 and 1973
   c) Average annual rate of bluff retreat between 1956 and 1973

4. Bluff composition

5. Bluff height

6. Bluff slope

7. Vegetative cover on the bluff slope

8. Hydrological phenomena within the bluff

9. Shoreline orientation

10. Beach width
    a) July
    b) August

11. Man-made "protective" structures

12. Present condition of the bluff

13. Additional comments

Site 88

1. a) Muskegon
   b) Montague, 15', 1959
   c) NW corner/sec. 23/T12N,R18W

2. a) 1837
   b) 3,098.7 ft.
   c) 128 ft.
   d) 1.07 ft.

3. a) 2,933.8 ft.
   b) 36.9 ft.
   c) 2.17 ft.

4. Dune sand

5. 30 ft.

6. 31½-37 degrees

7. None

8. None

9. N14W

10. a) None
    b) None

11. Groins extend north and south along the base of the bluff. A seawall is built along the property adjacent and north of the site line. Powers indicated no structures here in 1956.

12. Erosion is severe

13. Small debris slides or sand runs occur on the bluff slope whenever anything disturbs the surface or base of the slope. The dry, cohesionless, sand grains move downslope in thin surface layers. There is no nip at the base of the slope.

Site 89

1. a) Muskegon
   b) Montague, 15', 1959
   c) The original chained distance was from the NE corner/ sec. 31/T11N,R17W; however, in Powers' notes, a measurement is indicated for the distance to the bluff's edge from the intersection of McMillan Road and Scenic Drive.

2. a) 1837
   b) 4,488 ft.
   c) 169 ft.
   d) 1.41 ft.

3. a) 679 ft. - from the intersection of McMillan Road and Scenic Drive.
   (In 1956 Powers had measured this distance as 675 ft. Material definitely has not been added to the bluff. The bluff slope is presently stable and appears to have been so for some years. It is assumed that there has been no loss of bluff since 1956.)
   c) 0 ft.
   d) 0 ft.

4. Medium sand with scattered pebbles

5. 45 ft.

6. 30-37 degrees

7. Vegetative cover of small trees, bushes and grasses

8. None

9. N27W

10. a) 10 ft.
    b) 4 ft.

11. Permeable groins extend lakeward at the site and to the north and south (these did not exist in 1956). From one-hundred yards south of the site-line no groins occur for another 40 yards and erosion is severe here. This erosion appears to be precipitated by refraction of incoming waves off of an impermeable wooded groin at the southern limit of this 40 yard shoreline stretch.

12. Stable. A two-foot nip is cut into the base of the slope.

13. Since wave swash may now reach the bluff's base during periods of gusty winds, the bluff appears to be at a critical stage. During a storm waves could become very destructive on the bluff slope, removing much of the vegetation which is now acting as a sediment stabilizer.

Site 101

1. a) Ottawa
   b) Holland, 15'. 1929
   c) S¼ post/sec. 16/T5N,R16W

2. a) 1832 ft.
   b) 924 ft.
   c) 66 ft.
   d) 0.53 ft.

3. a) 849 ft.
   b) 9 ft.
   c) 0.53 ft.

4. 2-3 ft. wind-blown sand
   28 ft. medium to coarse sand; mostly horizontally bedded, some crossbedding

5. 30 ft.

6. 30-34 degrees; step-like

7. None

8. None

9. N-S

10. a) None
    b) None

11. None

12. Unstable and retreating. Sand runs (debris slides) occur on the slope whenever anything disturbs the surface of the bluff slope.

13. Any nip carved by waves in the base of the bluff is quickly covered by sand sliding down from upslope.

Site 106

1. a) Allegan
   b) Fennville, 15', 1928
   c) N¼ post/sec. 30/T2N,R16W

2. a) 1831
   b) 1,051.38 ft.
   c) 130 ft.
   d) 1.03 ft.

3. a) 918.5 ft.
   b) 2.88 ft.
   c) 0.17 ft.

4. 5 ft. fine sand and gravel
   50 ft. gray till, clayey with pebbles and scattered cobbles

5. 55 ft.

6. 35-49 degrees

7. Grass and small trees cover the slope with the exception of a 10-12 foot thick section six feet from the top.

8. Water percolates out from the bluff slope at the till and sand and gravel interface.

9. N15E

10. a) 8-10 ft.
    b) None

11. None except for a steel retaining wall which is leaning lakeward 150 feet north of the site line.

12. It is relatively stable along the upper edge of the bluff but evidence of base erosion and slumping and block gliding on the slope exists. Wave swash reaches the base of the slope. A four-foot nip is cut into a till slump or glide block at the base of the slope.

13. A local resident said that this particular site has been relatively stable for the last 15-20 years, but back then, however, a major collapse and down sliding occurred. The slope form appears to reveal previous downward movement of till blocks on the bluff slope.

Site 109

1. a) Van Buren
   b) South Haven, 15', 1928
   c) NW corner/sec. 15/T1S,R17W

2. a) 1837
   b) 995.94 ft.
   c) 348 ft.
   d) 2.74 ft.

3. a) 607.5 ft.
   b) 40.44 ft.
   c) 2.38 ft.

4. 5½ ft. sand, no pebbles
   1 ft. sand and gravel
   34 ft. gray, massive clay till with pebbles; much of this part of the slope is covered by a mixture of till and sand and gravel which has slid down from upslope

5. 41 ft.

6. Near vertical from the top to 7½ ft. into the till; the remaining slope measures 35-40 degrees

7. None

8. Water seepage along the interface of till and sand and gravel

9. N13E toward the north
   S28W toward the south

10. a) None
    b) None

11. Concrete slabs are placed at the base of the bluff adjacent and south of the survey point. The slope here is more gentle and portions are covered by vegetation (largely grasses) but slumping and block gliding have occurred near the top of the bluff. The only structure to the north is a steel seawall 75 yards from the site.

12. Erosion is severe. Much of the lower two-thirds of the slope is covered by material which has slid down from above. A four-foot nip is cut into in-situ till at the base of the slope. Erosion is more severe immediately to the north of the site line and the volume of the slope material is much less and the slope steeper than at the site line.

Site 109 (continued)

13. The site is located approximately one mile south of the jetties and waterworks intake at the South Haven harbor entrance. From a point one-third of a mile south of the survey point the shoreline to the north curves noticeably inland until the harbor jetties are reached. Erosion along this stretch is severe (U.S. Department of the Army, 1971a, p. 86).

Site 111

1. a) Berrien
   b) Benton Harbor, 15', 1927
      Benton Heights, 7½', 1970
   c) SE corner/sec. 21/T3S,R18W

2. a) 3915.5 ft.
   This figure is 15.5 feet greater than that measured by Powers in 1956. The bluff is at least 70 feet in height at this location. No aggradation has taken place. Except for minor slumping the bluff appears to be very stable as is evident by the dense vegetative cover and medium size trees on the slope. It is not known whether an error was made by Powers or this investigator but it will be assumed that there has been no erosion from the upper edge of the bluff since 1956.
   b) 0 ft.
   c) 0 ft.

4. 6-7 ft. sand with widely scattered very small pebbles
   60-62 ft. gray pebbly clay till
   2-3 ft. sand nip three feet wide in remnants of a low foredune

5. 70 ft.

6. 30-45 degrees on the till
   55 to near 90 degrees on the upper sand

7. Wooded with relatively dense ground cover

8. Water lay in linear depressions on the mid-slope where old slump blocks cover the bluff face. The water may have seeped out from the sand and till interface although this was not evident on the days on which the site was visited.

9. N35E

10. a) 39 ft.
    b) 23-25 ft.

11. None

12. Stable. Minor mass-wasting appears to have taken place sometime in the last several years near the top of the bluff. An exposure three to five feet in vertical extent is visible straddling the contact between the upper sand and the till.

Site 111 (continued)

13. Examination of the slope form and tree shapes below the exposure mentioned in number 12 indicates that major slumping took place an undetermined number of years ago. Several shallow, vegetated, linear depression scars lie parallel to the bluff's edge on the upper third of the till profile. Water saturated several of the depressions. Many trees on this area have bends in their trunks two-to-two and one-half feet from their bases.

The small sand nip at the base of the slope is probably the remnants of a low dune constructed during a low water stage of Lake Michigan.

Site 112

1. a) Berrien
   b) Benton Harbor, 15', 1927
      Benton Heights, 7½', 1970
   c) SE cor/sec 3/T3S,R18W

2. a) 1830
   b) 1914 ft.
   According to Powers, bluff loss amounted to only a total of 25 feet in the 126 years until 1956. This investigator is convinced that Powers' survey measurement was incorrect. At his site 113, approximately one mile south of the present study site, the 1956 survey revealed a bluff loss of 354 feet since the original land survey. Two and one-half miles north of site 112 Powers calculated a bluff retreat total of 390 feet at his site 111 for the period 1830 to 1956. The shoreline is virtually straight between sites 113 and 111 - this would probably not have not been the case if the bluff at site 112 had only retreated 25 feet since 1830.

   The 1927 topographic map reveals a distance of about 1,450 to 1,475 feet to the bluff's top edge and approximately 1,700 feet to the bluff's base from the section corner. The 1970 topographic map of the area reveals a distance of about 1,325 feet to the bluff's upper edge whereas the distance was 1,550 feet to its base.

   On the 1927 topographic quadrangle the M-139 highway marked both the eastern extent of sections 31 and 6. The section 31 segment was offset to the east of the section 6 segment. Since then, however, the section 31 highway segment has been shifted westward and aligned with the section 6 road segment.

   The old road coinciding with the eastern limit of section 31 is evident on Powers' 1950 areal photo but is not revealed presently in the field. Because of this situation, a 1973 survey was not performed.

3. ---

4.

12-15 ft.	gray clayey till with pebbles
2 ft.	alt. beds of fine sand and gravel
2 ft.	fine to silty sand
6-7 ft.	gray clay with small pebbles
12-15 ft.	no exposure; till has slid over the bluff face
17 ft.	silty to clayey sand, with scattered clay balls
20 ft.	no exposure; slope is covered by till slide
12 ft.	med. sand with numerous small pebbles
11-12 ft.	no exposure; till slide covers slope
12 ft.	slumped or glided till block covers med. sand containing small pebbles

Site 112 (continued)

Two-hundred yards north of the site is an exposure at the base of the slope of bedded and crossbedded sand with pebble inclusions and gravel layers. It is approximately 30 feet thick where exposed.

5. 100-110 ft.

6. 35 to near 90 degrees

7. Much of the slope is devoid of vegetation. Small bushes, grasses and several trees are growing on a linear ridge between gullies extending down the center of the slope area.

8. Water percolates out from the area between the two clay layers. Two drain pipes extend out from the top of the bluff face.

9. N36E

10. a) 25 ft.
    b) 20 ft.

11. None

12. Unstable and eroding; see number 13 below

13. The study site is at the southern margin of a 225 foot wide indentation into the bluff's upper edge. On either side of the concave area the top bluff line extends lakeward another 30 feet. This difference does not exist at the base of the slope.

    The slope extending downward along the 225 foot wide concave area is extensively gullied.

    A local resident stated that the bluff edge and slope has receded each year along the 225 foot section. A staircase had to be continually repaired due to the unstable slope. There are no steps presently. This concave stretch along the top of the bluff has been here since at least 1956 when the resident moved to the property. The 1927 topographic map shows a similar feature, although its southern margin had not yet receded to the section line and the present study site.

    According to the property owner, the straight line portion of the bluff 25 feet south of the study point had been much steeper in 1960. Presently its slope is 39-40 degrees. She stated that in 1966 the water table in the area had changed and water began to seep out from the bluff. (This change was attributed to heavy building construction taking place in the vicinity.)

A large till block had slumped down several feet from the upper edge of the bluff 200 feet south of the study site this past June. The owner of the lot indicated that water frequently seeped out from the upper bluff slope.

Site 115

1. a) Berrien
   b) Benton Harbor, 15', 1927
   c) SW corner/sec. 3/T5S,R19W
   A curve was added to the road at this point. At a point in the center of the old abandoned road segment a sunken metal post under a small metal cover marked by a painted yellow X was found. It is believed that this post indicated the location of the section corner.

   The site is 400 feet north of the northern limit of the case study bluff segment and much of the description presented here applies to that location.

2. a) 1829
   b) 957 ft.
   c) 142 ft.
   d) 1.11 ft.

3. a) 734 ft.
   b) 81 ft.
   c) 4.76 ft.

4. | | |
   |---|---|
   | 6 ft. | fine silty sand, pebbles strewn on top |
   | 38 ft. | medium clean sand with a few scattered pebbles, crossbedded in places but predominately horizontally bedded |
   | 10 ft. | fine sand and silt |
   | 6 ft. | covered |

   This profile was abstracted from Powers' field notes as the present condition of the bluff prohibited a safe examination of the sediments.

5. 60 ft.

6. 30-35 degrees; near vertical in the upper 3-4 ft.

7. None

8. None

9. N27E

10. a) None
    b) None

11. A half star shaped low breakwater was built three years ago at the water's edge immediately adjacent and south of the survey site line. Another breakwater is positioned about 75 yards to the north. A concrete barrier, built last year, protects the bluff 850 feet south of the study location. Lakeward of this barrier is the de-

caying remains of a wooden permeable breakwater built in the 1950's.

12. Erosion is extremely severe. The slightest disturbance on the slope will cause sand runs on the bluff face.

13. The study site lies in a concave inland segment of the shoreline bluff extending about 425 yards in length. This bluff segment lies approximately four miles south of the jetties at the St. Joseph harbor. Littoral drift is southerly but the jetties effectively prohibit movement of sediment south of the harbor entrance (U.S. House of Representatives, 1958, p. 4).

VARIATIONS
IN
WATER LEVEL AND PRECIPITATION
IN THE
LAKE MICHIGAN BASIN

By

William R. Buckler

A RESEARCH PAPER

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INTRODUCTION

Much concern in the last several years has been focused on shoreline erosion in the Great Lakes. This attention has been fostered to a large extent by man's intense development of much of the shoreline. This development depends on the stability of the lake system's levels. The conditions giving rise to the present erosion and resulting economic losses along the eastern shoreline of Lake Michigan are related to both the unconsolidated glacial sediments composing the lake shore areas and the nonperiodic trends in the regional climate. In the continuing natural processes which act on the Lake Michigan shoreline, erosion occurs at all stages of lake levels. During periods of high levels, however, the rate is accelerated and the extent is greatly expanded.

PURPOSE

The purpose of this paper is to describe and account for those natural and man-created factors which affect Lake Michigan's fluctuating water level. Precipitation rates over the Lake Michigan-Huron basin will be considered in detail since these rates are probably most responsible for fluctuations in the lake level. An attempt also will be made to explain the cause for the long-term and annual changes in the precipitation amounts over the basin.

Mid- and upper-level tropospheric air flows are generally responsible for mid-latitude weather phenomena. Therefore, mean monthly 500 mb air flow patterns over the Michigan-Huron basin will be examined for the period 1950 to 1971 in order to determine if the varying precipitation rates can be at least partially explained due to changing air flow patterns.

BASIC DATA

Basic data relating to the Great Lakes water levels are routinely compiled by the National Ocean Survey, Lake Survey Center, formerly under the U. S. Corps of Engineers but presently under the auspices of the National Oceanic and Atmospheric Administration (NOAA) in the U. S. Department of Commerce. Mean monthly and annual Lake Michigan-Huron water levels and diversions into and out of the lakes by way of the St. Marys and St. Clair Rivers, respectively, along with the mean annual precipitation amounts for the basins were obtained from the Lake Survey Center for the period of record. Reliable basin precipitation data prior to 1900 but after 1874, not available from the Center, were obtained from Day (1926). Dependable Lake Michigan-Huron precipitation information before 1874 is unobtainable. The U. S. Commerce Department's monthly publication - Climatological Data, National Summary - was utilized in order to record and plot the mean monthly 500 mb surface wind flow directions and trough axis positions for the period of record over the

Lake Michigan-Huron basin. Mid- and upper-tropospheric air flow data have only been published since 1950.

LAKE MICHIGAN-HURON BASIN CHARACTERISTICS

Prior to the onset of late Cenozoic glaciation the present Lake Michigan basin consisted of a series of subsequent stream valleys which were related to the general drainage of the mid-continent (Dorr and Eschman, 1970). The four major ice advancements enlarged the existing lowlands leaving behind, upon retreat of the ice masses, several proglacial lakes. The present-day Lake Michigan lies in the west-central portion of the Great Lakes basin, south of Lake Superior and west of Lake Huron (Figure 1). Hydrologically Lakes Michigan and Huron are considered to be a single lake due to their wide and deep connection at the Straits of Mackinac. Their combined drainage area of 142,700 square miles includes 45,300 square miles of water surface. The average depth of Lake Huron is 195 feet, whereas the average for Lake Michigan is 279 feet, with a maximum depth of 923 feet. Their combined volume of water totals 2,029 cubic miles (Corps of Engineers, 1971).

Direction of currents in the Straits alternates from east to west depending on barometric pressure and wind direction; however, the net flow is eastward from Lake Michigan to Lake Huron (Great Lakes Basin Commission, 1972). Since 1848 water has been diverted from Lake Michigan to the Mississippi River drainage basin via the Chicago drainage canal. The St. Marys River drains into Lake Huron at the

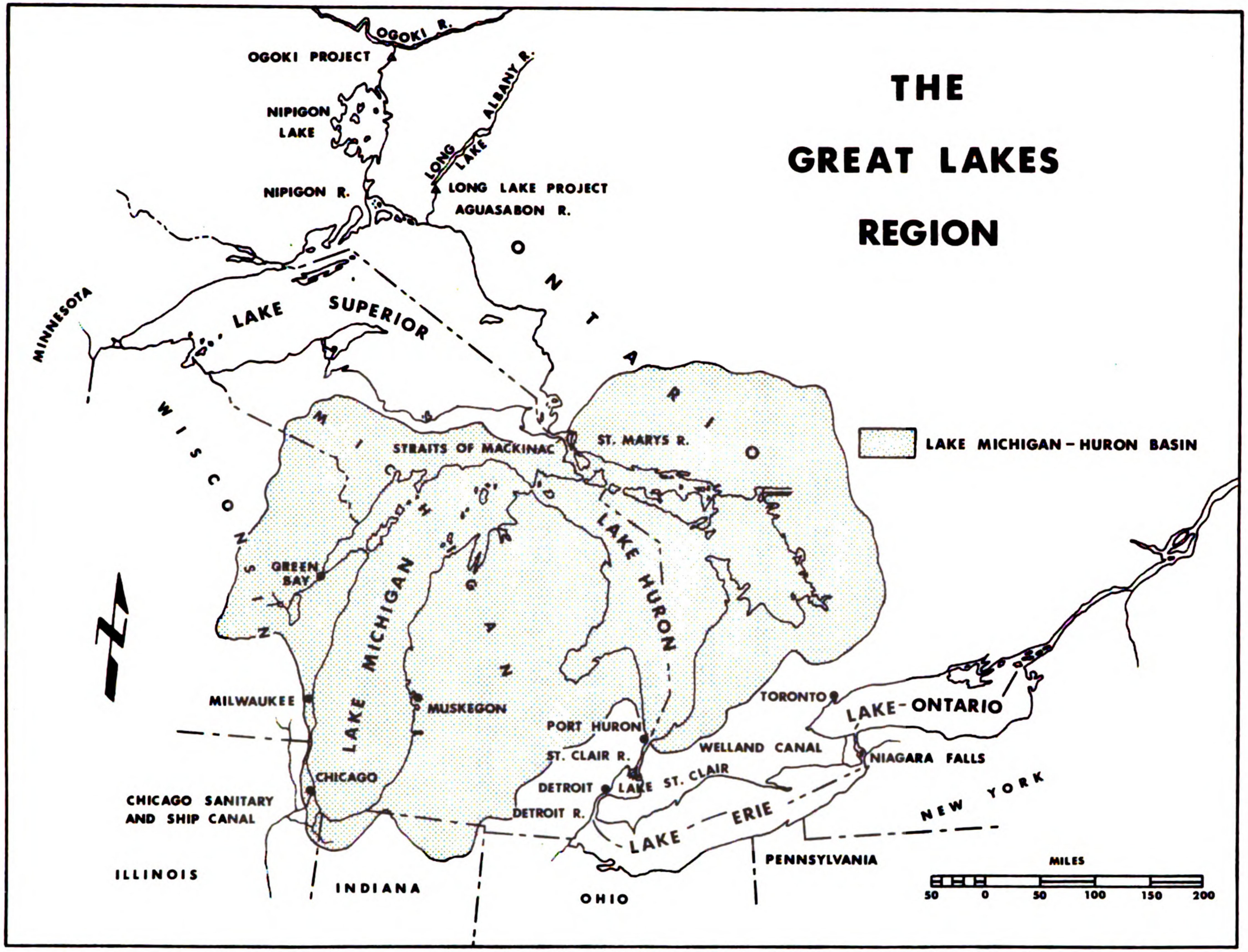


Figure 1: The Great Lakes region.

north from Lake Superior and the St. Clair River diverts water out of the basin at the south into the lower Great Lakes.

LAKE MICHIGAN-HURON WATER SUPPLIES

At a given time the water level in the Lake Michigan-Huron basin depends primarily on whether the lakes are receiving more or less water than they are giving up. "The water supply consists of precipitation on the lake surface, runoff from the lake's drainage area, inflow from a lake above, diversion of water into the basin, and ground water inflow. Water is removed from the lake by evaporation, diversion to another drainage basin, outflow from the lake through its natural outlet, and ground water seepage."

DeCooke (1968 a,b), Laidly (1962) and the Great Lakes Basin Commission (1972), among others, have expressed the interrelationships of these factors in the form of a "hydrological balance equation":

$$AC = (P + R + I + Di + Gi + Ic) - (E + O + Do + Gs + Ic)$$

where

AC = change in the amount of water stored in the lake basin

P = precipitation on the lake's surface

R = runoff from the drainage basin

I = inflow from a lake above

Di = diversion into the lake from another basin

Gi = inflow of ground water

E = evaporation from the lake surface

O = outflow from the lake through its natural outlet

Do = diversion from the lake into another basin

Gs = groundwater seepage

Ic = ice blockage of outlet channel

In addition to these hydrological factors which contribute to a specific lake level, several subordinate non-hydrological factors affect the Lake Michigan-Huron level although not in themselves changing the volume of water in the basin. These factors include crustal movement, wind, barometric pressure changes, and tides and are discussed in the appendix.

Precipitation and Runoff

Approximately 70 percent of the contemporary variation in the Lake Michigan-Huron level is related to basin precipitation (Muller et al, 1965; Brunk, 1960). The relationship is not simple for the many variables in the "hydrological equation" and the vastness of the Lake Michigan basin play supporting roles. Nevertheless, over the long run, the water level rises and falls in relation to rises and falls in the precipitation rates over the drainage area (Table 1 and Figure 2), and it is these fluctuations which are the subject of this paper.

The U. S. Lake Survey computes the monthly and annual precipitation amounts over all of the Great Lakes from data supplied by the U. S. National Weather Bureau and the Meteorological Branch of the Department of Environment, Canada. The record extends back to 1900 for the Lake Michigan-Huron basin. Day (1926) made a comprehensive study of the precipitation regimes in the Great Lakes area for the

Table 1: The mean annual water level and precipitation amount and their departures from normal in the Lake Michigan-Huron basin, 1875-1972.

Year	Mean Annual Water Level (in feet)	Departure From the Normal (in feet)	Mean Annual Precipitation Amounts (in inches)	Departure From the Normal (in inches)
1875	579.90	1.42	34.40	2.44
1876	580.94	2.46	37.88	5.92
1877	580.65	2.17	34.34	2.38
1878	580.40	1.92	37.13	5.17
1879	579.52	1.04	33.46	1.50
1880	579.96	1.21	39.21	7.25
1881	580.07	1.59	39.81	7.85
1882	580.42	1.94	38.40	6.44
1883	580.69	2.20	39.42	7.46
1884	580.90	2.42	37.67	5.71
1885	581.06	2.58	35.77	3.81
1886	581.28	2.80	33.61	1.65
1887	580.63	2.15	30.66	-1.30
1888	579.98	1.50	28.93	-3.03
1889	579.48	1.00	29.44	-2.52
1890	579.31	.83	33.47	1.51
1891	578.74	.26	30.88	-1.08
1892	578.58	.10	34.95	2.99
1893	578.76	.28	34.01	2.05
1894	578.96	.48	29.06	-2.90
1895	578.10	- .38	26.52	-5.44
1896	577.79	- .69	31.58	- .38
1897	578.40	- .08	32.87	.91
1898	578.55	.07	33.50	1.54
1899	578.56	.08	30.24	-1.72
1900	578.57	.09	32.31	.35
1901	578.83	.35	28.91	-3.05
1902	578.47	- .01	32.51	.55
1903	578.61	.13	33.24	1.28
1904	579.09	.61	31.04	- .92
1905	579.21	.73	33.75	1.79
1906	579.23	.75	31.90	- .06
1907	579.30	.82	29.79	-2.17
1908	579.21	.73	29.16	-2.80
1909	578.69	.21	31.35	- .61
1910	578.37	- .11	28.09	-3.87
1911	577.83	- .65	32.37	.41
1912	578.29	- .19	32.24	.28
1913	578.92	.44	29.02	-2.94
1914	578.47	- .01	28.70	-3.26
1915	577.89	- .59	29.37	-2.59

Table 1: Continued

Year	Mean Annual Water Level (in feet)	Departure From the Normal (in feet)	Mean Annual Precipitation Amounts (in inches)	Departure From the Normal (in inches)
1916	578.60	.12	33.70	1.74
1917	579.34	.86	27.78	-4.18
1918	579.55	1.07	31.06	- .90
1919	579.07	.59	30.47	-1.49
1920	578.70	.22	28.43	-3.53
1921	578.27	- .21	31.72	- .24
1922	578.13	- .35	31.80	- .16
1923	577.52	- .96	28.24	-3.72
1924	577.27	-1.21	30.81	-1.15
1925	576.39	-2.09	26.21	-5.75
1926	576.31	-2.17	33.09	1.13
1927	577.18	-1.30	31.40	- .56
1928	578.17	- .31	35.50	3.54
1929	579.65	1.17	31.53	- .43
1930	578.85	.37	24.37	-7.59
1931	577.07	-1.41	30.68	-1.28
1932	576.51	-1.97	31.77	- .19
1933	576.25	-2.23	30.49	-1.47
1934	575.94	-2.54	27.31	-4.65
1935	576.34	-2.14	28.76	-3.20
1936	576.50	-1.98	29.30	-2.66
1937	576.45	-2.03	30.52	-1.44
1938	577.14	-1.34	33.75	1.79
1939	577.58	- .90	29.71	-2.25
1940	577.16	-1.32	33.53	1.57
1941	577.09	-1.39	33.03	1.07
1942	577.81	- .67	34.77	2.81
1943	578.77	.29	32.94	.98
1944	578.66	.18	29.94	-2.02
1945	578.57	.09	36.18	4.22
1946	578.68	.20	28.61	-3.35
1947	578.59	.11	33.64	1.68
1948	578.44	- .04	28.24	-3.72
1949	577.40	-1.08	31.11	- .85
1950	577.58	- .90	33.70	1.74
1951	579.14	.66	38.02	6.06
1952	580.30	1.82	30.68	-1.28
1953	579.79	1.31	30.61	-1.36
1954	579.47	.99	37.44	5.48
1955	579.10	.62	28.58	-3.38

Table 1: Continued

Year	Mean Annual Water Level (in feet)	Departure From the Normal (in feet)	Mean Annual Precipitation Amounts (in inches)	Departure From the Normal (in inches)
1956	578.18	- .30	29.19	-2.77
1957	577.60	- .82	32.95	.99
1958	577.01	-1.47	26.15	-5.81
1959	576.76	-1.72	37.55	5.59
1960	578.28	- .20	33.72	1.76
1961	577.97	- .51	30.97	- .99
1962	577.45	-1.03	27.79	-4.17
1963	576.48	-2.00	26.12	-5.84
1964	575.66	-2.82	29.81	-2.15
1965	576.43	-2.05	36.50	4.54
1966	577.25	-1.23	29.88	-2.08
1967	577.69	- .79	34.99	3.03
1968	578.18	- .30	34.11	2.15
1969	579.01	.53	32.27	.31
1970	578.93	.45	33.90	1.94
1971	579.36	.88	30.67	-1.29
1972	579.66	1.18	35.14	3.18

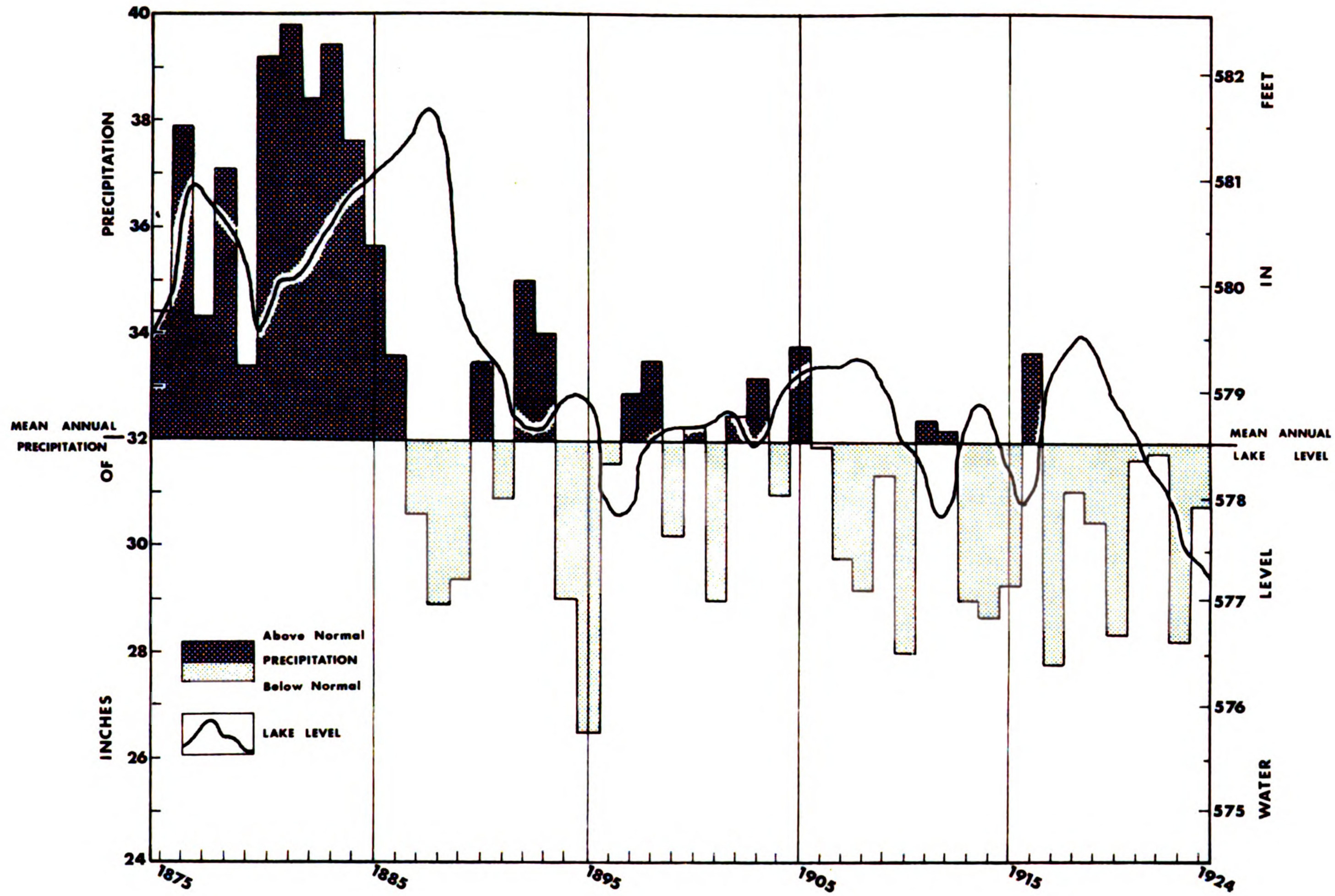


Figure 2: The average annual Lake Michigan-Huron water levels and basin precipitation amounts, 1875-1972.

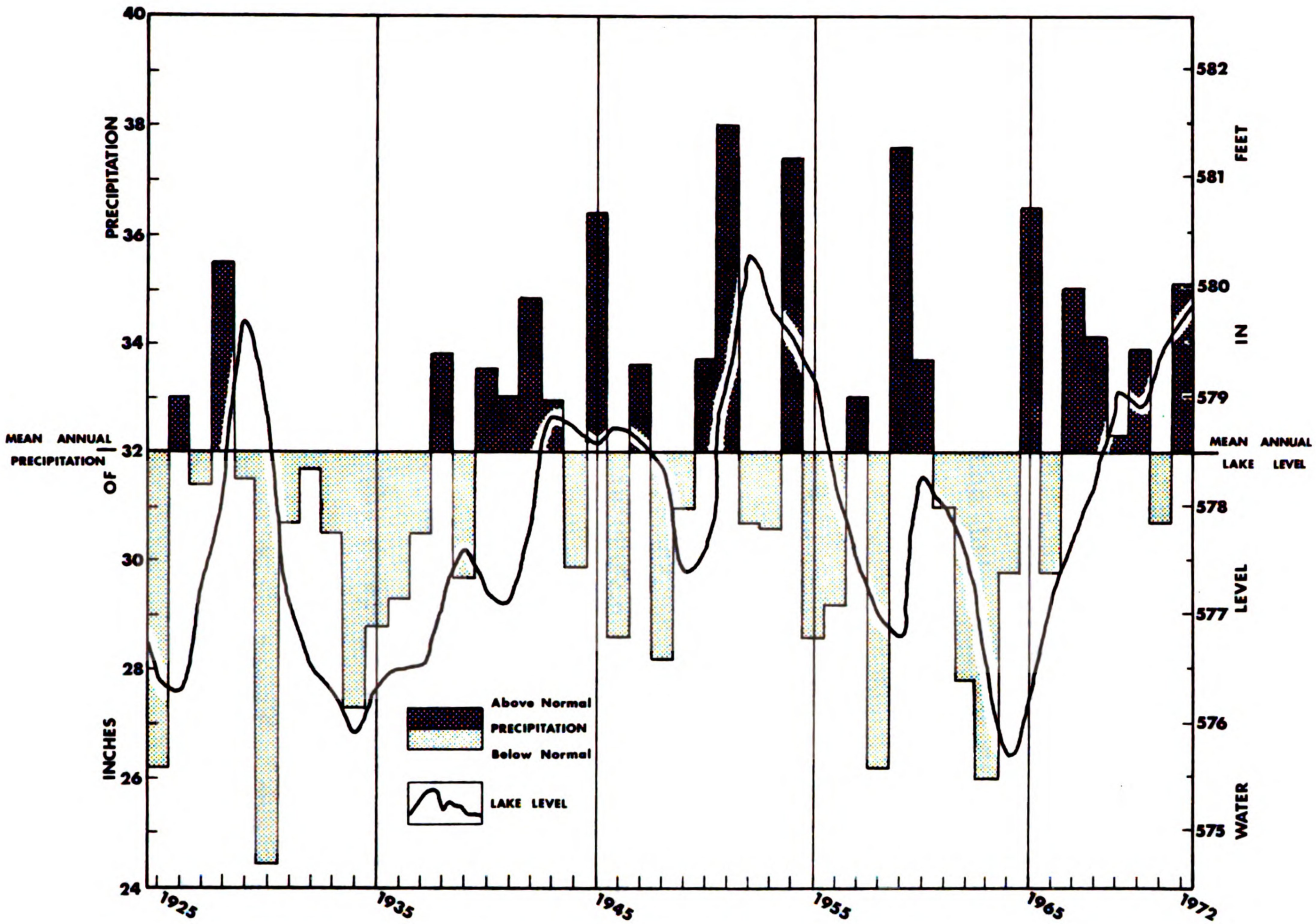


Figure 2: Continued

years 1875 to 1924. He noted that when official daily weather statistics were initially collected in the late 1870's more stations per unit area were established in the Great Lakes region than in other parts of the country. Even though he used a total of only 39 control stations for the Lake Michigan-Huron basin, as compared to the present total of approximately 200, his results are considered representative (Brunk, 1962). Indeed, a comparison for the period 1900 to 1924 between the Lake Survey figures and Day's figures reveals only a 2.5 percent higher precipitation value in Day's yearly averages. Day's computed annual precipitation rates for 1875 to 1899 are utilized in this study to extend the Lake Survey Center's figures back to 1875. The record for the Lake Michigan-Huron water level will assume an initiation date of 1875 for this paper. This will allow favorable comparison between the two sets of variables (Table 1).

Between 1875 and 1972 the mean Lake Michigan-Huron level was 578.48 feet[1] while the average annual precipitation over the basin was 31.96 inches. This compares to the 1860 to 1972 figure of 578.69 for the lake level. The annual average precipitation for the Lake Huron basin was 32.08 inches while that of the Lake Michigan basin was 31.84 inches. Utilizing only the Lake Survey data, 1900 to 1972, the Lake Michigan-Huron level averaged 578.08 feet whereas

[1]All water levels are referenced to the 1955 International Great Lakes Datum.

the annual mean precipitation measured 31.29 inches.

For the period of record, monthly mean levels for Lake Michigan-Huron have varied from a low of 575.35 feet in March, 1964, to a high of 581.94 feet in June, 1886, a difference of 6.59 feet. Both Freeman (1926) and Day (1926) cite the Board of Engineers on Deep Waterways report (Secretary of War, 1900) referring to the early levels of the Great Lakes. The highest authenticated annual stage of Lake Michigan - 584.3 feet - occurred in 1838 and was 5.61 feet above normal, 4.64 feet above the 1972 level.

Even though precipitation varies considerably from year to year, yearly totals oscillate around a norm. Periods of abundant precipitation are usually followed by others of lower rainfall. "Since 1875 21 periods have occurred, from one to nine years in length, in which precipitation amounts were below average, separated by intervals of above normal precipitation of from one to twelve years in duration. In total, nine different periods of high water levels and eight distinct intervals of below average Lake Michigan-Huron levels have occurred since 1875 (Figure 2)."

"In the Great Lakes drainage system considerable lag occurs between precipitation and fluctuations of lake level. Much of this is probably due to the unconsolidated glacial material which comprises much of the drainage basin (Freeman, 1926). The sand, gravel and till, when unfrozen, absorb and retain much of the rainfall as it falls." Percolation may take several years as the water migrates to the various stream beds and into the lakes. "As reported by Richards (1969), Brunk (1960) suggests that precipitation of the present and preceding year contributes nine percent and 37 percent, respectively, to Lake Michigan-Huron levels, while precipitation of two and three years earlier contribute 34 and 20 percent, respectively."

The excess rainfall in 1928 over the basin increased the Michigan-Huron level by 1.48 feet. "In 1930, however, the greatest deficit in precipitation for the period of record occurred and caused a lowering of the level by 1.78 feet." The 1959 surplus initiated a rise of 1.52 feet in 1960 although the water level was still below normal. A deficit of 4.17 inches in the 1962 yearly mean precipitation amount was followed by a lowering of the lake by about a foot in 1963. A further deficit of 5.84 inches in 1963 led to an additional drop in the following year of .82 foot. The above normal precipitation in 1972 is expected to cause an increase in the annual Michigan-Huron level by at least .5 foot.

Approximately two-thirds of the Lake Michigan-Huron basin is covered by land area. Although the annual amount of precipitation has a large bearing on the total runoff in the basin, seasonal distribution of precipitation and the north-south temperature gradient are equally important (Pentland, 1968, p. 328). "Runoff is generally at its peak during March, April and May as the winter snow accumulation melts and while evaporation rates from the land surface are low. Runoff is least in August and September due to the high evapotranspiration losses. Increasing runoff in October and November occurs because of the sharp drop in evapotranspiration (Tables 2 and 3).

Above average rainfall can occur in the summer season without adversely affecting runoff and lake levels if it is evenly distributed. The abundant rainfall would go mainly into vegetative growth. Lesser amounts of rainfall, however, may produce much greater runoff if it falls on saturated or frozen ground. A situation in 1954 is considered unique. Heavy October rains resulted in immediate runoff which caused an October maximum in the Lake Michigan-Huron level, then held the next winter's water level up, but did not produce a rise in 1955 (Eichmeier, 1964, p. 20).

Since 30 percent of the Michigan-Huron surface is water, precipitation falling directly on the lake affects the lake level immediately. Since the late 1920's, however, there has been disagreement as to whether the rate of precipitation falling on the water surface is approximately equal to, less than, or greater than that falling on the remaining land surface of the drainage area.

Freeman (1926) believed that there was no difference in precipitation rates over the land and water surfaces. Using island and land station data in Lake Michigan for the years 1871 to 1927, Horton and Grumsley (1927) concluded that on Lake Michigan winter precipitation averaged 93 percent of that at shore stations and summer precipitation 94 percent

Table 2: The mean basin runoff in cubic feet per second per square mile, 1935-1964.

Month	Lake Michigan Basin	Lake Huron Basin
January	0.75	0.62
February	0.72	0.67
March	1.16	1.43
April	1.72	2.64
May	1.17	1.70
June	0.80	0.94
July	0.57	0.65
August	0.49	0.44
September	0.54	0.46
October	0.60	0.61
November	0.69	0.86
December	0.60	0.83
ANNUAL	9.81	11.85

Source: Pentland, R.L. 1968. Runoff characteristics in the Great Lakes basin. Proc., 11th Conf., Great Lakes Res., Intern. Assoc. Great Lakes Res., p.331.

Table 3: The average monthly runoff in inches depth on lake, 1935-1964.

Month	Lake Michigan Basin	Lake Huron Basin
January	1.77	1.61
February	1.54	1.58
March	2.73	3.71
April	3.92	6.63
May	2.76	4.41
June	1.83	2.36
July	1.34	1.69
August	1.16	1.14
September	1.23	1.16
October	1.41	1.58
November	1.57	2.16
December	1.41	2.16
ANNUAL	22.67	30.19

Source: Great Lakes Basin Commission. 1972 (Final Draft). Levels and flows. Appendix No.11, Great Lakes Basin Framework Study. Ann Arbor, Michigan, p.76.

of the shore station averages. They credited this reduction to the lower thunderstorm frequencies and intensities over the lake. Day (1926) found that less precipitation was registered in gages on islands in northern Lake Michigan than on the adjacent mainland. Nevertheless, he attributed the difference to increased wind velocities over the lake materially lessening the catch of the gages. He therefore assumed the precipitation over the land and the water was approximately equal. As reported by Changnon (1976), Kohler (1959) and Blust and DeCooke (1960) have made similar statements more recently. Brunk (1962) noted that the yearly amounts of precipitation over the Michigan-Huron basin land and water surface were of little difference.

In a comprehensive Illinois study Changnon (1967, 1968) estimated that the average precipitation over Lake Michigan is six percent less than that over the land portion of the basin. He believes that "the results of this study are more accurate than the earlier findings because they are based on more detailed information from recent lake precipitation studies, a greater knowledge of the effects of the lake on the atmosphere and a greater volume of weather data than existed when the previous studies were made" (1968, p.1).

> The significance of the accuracy in correctly estimating or calculating lake precipitation can be realized by comparing the basin water yield based on the assumption that there was no lake difference with that based on the six percent difference. If the average value is 31.12 inches, then the average precipitation over the entire basin produces 37,009 billion gallons of water annually. If the average basin

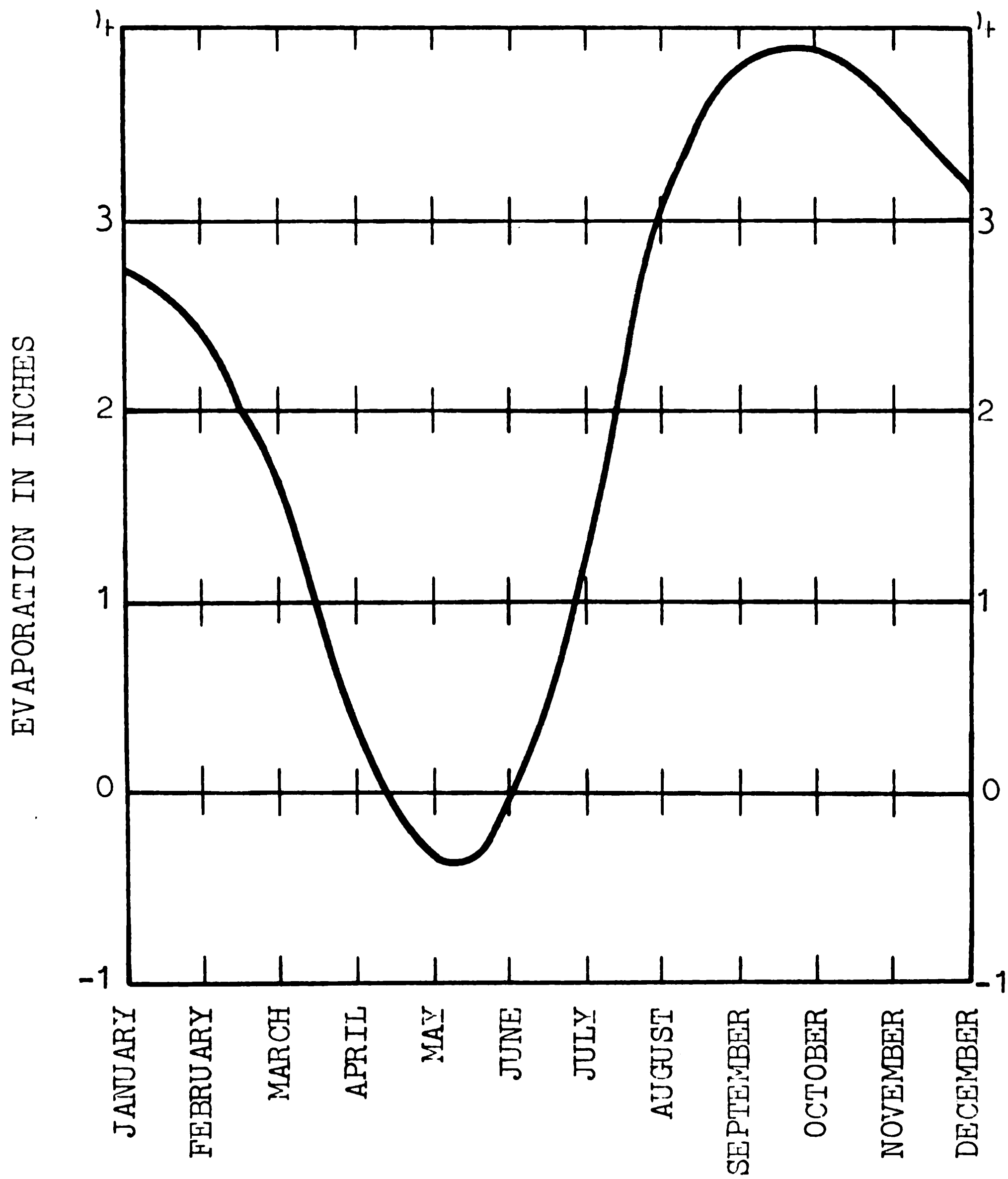
> precipitation is compiled using the lake value that is six percent lower than the land value, the water produced annually by precipitation is 36,309 billion galllons, a difference of 700 billion gallons annually. This difference between the two values represents 2,970 cfs (p. 44).

Evaporation

Although precipitation plays the major role in modifying contemporary lake levels, evaporation also plays a significant role. "The importance of considering evaporation becomes plain when one realizes that there are long periods in each year during which more water goes up into the air from the Great Lakes by evaporation than the amount which flows down the Niagara or St. Lawrence Rivers" (Freeman, 1926, p.XVII).

Conditions which affect evaporation from the Great Lakes are very different from those which control evaporation from ordinary lakes and reservoirs because of their vast size and heat storage capacity (Freeman, 1926). "In winter, when the lake surfaces are relatively warmer than the enveloping air masses, evaporation occurs at a much more rapid rate than from the surface of ice or snow. Just the reverse is true in early summer. During this period the water of the Great Lakes is usually colder than the surrounding air. This condition greatly retards evaporation." Freeman pointed out that the greatest evaporation takes place in the fall or winter and the smallest in the late spring and early summer over the Great Lakes district (Figure 3)."

Because of its vast size and storage capacity and lack of over-water data, truly accurate evaporation rates have



Source: Great Lakes Basin Commission. 1972 (Final Draft). Levels and flows. Appendix No. 11, Great Lakes Basin Framework Study. Ann Arbor, Michigan, p.80.

Figure 3: The computed average annual evaporation for Lake Michigan-Huron.

not been determined for Lake Michigan-Huron. By subtracting the measured inflow from the measured outflow, Freeman (1926, pp. 142-143) estimated an average annual evaporation rate of 25.47 inches for the water surface of Lake Michigan-Huron. By another computation based on the vapor pressure differences of air and water and on the velocity of the wind he verified the previous "water budget" estimate with a "mass transfer" figure of 29.12 inches. "Energy budget" estimates and evaporation pan observations have been utilized but have yet to be proven effective in Lake Michigan-Huron evaporation studies (Richards, 1969, pp. 62-64; Bruce and Rodgers, 1962, pp. 54-65). Investigators have most often used the water budget and mass transfer methods. The Great Lakes Basin Commission (1972, p. 89) noted that the more recent investigators on Lake Michigan-Huron have corroborated Freeman's estimate of approximately 26 inches.

Diversions

Diversion of water to and from one drainage system into another has an effect on the water flows and the lake levels within the second system. A diversion to or from a single lake within a drainage basin has a consequence on those lakes upstream and downstream within the same system.

If water is continuously diverted into a drainage system from another, the receiving system will eventually convert this additional water into higher lake levels and greater outflow. The reverse is true if water is continuously diverted from a drainage system. A diversion into a particular lake within a chain of lakes, such as the Great Lakes, will cause an increase in outflow and water levels downstream while at the same time may cause increased water levels upstream. Both outflow and water levels upstream and downstream will decrease if water is diverted out of a lake within a particular drainage system.

Lake Michigan-Huron is affected by two primary diversions. Water is diverted out of Lake Michigan into the Mississippi River drainage system at Chicago while water is diverted into Lake Superior which is further upstream in the Great Lakes system.

A portion of the area originally draining into Hudson Bay by way of the Albany River now drains into northern Lake Superior (Figure 1). This was precipitated by the Long Lake and Ogoki projects. In 1939 water was diverted from the Kenogami River through Long Lake to help flush pulp logs through Long Lake and the Aguasabon River to Lake Superior. A hydroelectric power plant was constructed in 1948 on the Aguasabon River to utilize the increased flow. The Ogoki power project diverts water, initially draining to the north, through the Albany River to the south via the Little Jackfish River which flows into Lake Nipigon and thence into Lake Superior.

Since 1940 the water supply to Long Lake has averaged approximately 1,700 cfs. Of this, 1,450 cfs has been diverted to Lake Superior (Great Lakes Basin Commission, 1972, p. 93).

The Ogoki Reservoir has had an average inflow of 5,000 cfs since 1943. Approximately 4,000 cfs of this is diverted to Lake Superior (Great Lakes Basin Commission, 1972, p. 96). Kirshner (1968, p. 296) has estimated that the Ogoki-Long Lake diversions into Lake Superior have effected an increase downstream in Lake Michigan-Huron water levels of about .37 foot in spite of the regulatory works in the St. Marys River.[2]

The diversion of water into the Lake Michigan-Huron basin via the Ogoki-Long Lake projects is partially compensated for by diversion out of its basin by way of the Chicago Sanitary and Ship Canal. This canal was completed in 1900 and by 1910 had forced the abandonment of the Illinois and Michigan Canal, completed in 1848, which had first diverted water from the Lake Michigan drainage basin at Chicago. The present diversion includes water diverted directly from Lake Michigan in addition to water from the drainage basin in the Chicago area which normally would flow into the lake. As initially conceived, the diversion was for the purpose of dilution and subsequent flushing of sewage into the Des Plaines River which connected to the Mississippi River system. The water now also serves as a navigation route to the Illinois River from Lake Michigan.

Prior to 1938, up to 10,000 cfs of Lake Michigan water flowed through the canal but in 1938 the U. S. Supreme Court

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[2]Recently the Ogoki diversion project has been shut down.

limited the amount to 3,100 cfs. In 1967 this was revised upward to 3,200 cfs, 1,700 cfs of which is pumped for domestic and industrial use while the remainder includes the surface runoff which originally flowed into Lake Michigan and the water diverted directly from Lake Michigan for navigational purposes.

The effect of this diversion at Chicago on Lake Michigan-Huron is not an instantaneous one. Due to the great storage capacity of the basin considerable time is necessary for the readjustment of lake level because of the diversion. Ramey (1952 b, p. 4) estimated that it took five years for Lake Michigan-Huron to reach 94 percent of its ultimate lowering due to the diversion. Freeman (1926, p. 218) had estimated 91 percent of maximal lowering after five years. Presently, outflow from Lake Michigan-Huron at Chicago has lowered the water level approximately .23 foot (Kirshner, 1968, p. 296; Great Lakes Basin Commission, 1972, p. 98). With a greater diversion out of the drainage system in the early part of the century Freeman (1926, p. 218) estimated that the total lowering had been about .42 foot by 1926. The maximum lowering of Lake Michigan-Huron due to the Chicago diversion was attained in 1926 when the water level was lowered by .5 foot (Ramey, 1952 b, p. 4).

As was implied previously, water diverted into one lake, in a chain of lakes, affects all the water levels. This teleconnection is evident with respect to Lake Michigan-Huron and the Welland Canal. Water is diverted through this canal from Lake Ontario, two lakes downstream from the Lake Michigan-Huron basin. According to figures cited by Kirshner (1968, p. 296),this diversion ultimately has lowered the level of Lake Michigan-Huron by about .10 foot.

Inflow

Discharge from Lake Superior flows through the St. Marys River to Lake Huron, whose surface is 22 feet below that of the upper Great Lake. The rate of outflow from Lake Superior has averaged approximately 75,000 cfs. Since 1922 this discharge has been regulated by means of power and navigation canals and a grated dam at Sault Ste. Marie. In accord with international regulations the outflow from Lake Superior into Lake Huron is kept as close to natural conditions as possible, although the stage of Lake Superior is to be held as nearly as possible between elevation 600.5 and 602.0 feet. In addition, the discharge is to be so controlled at Sault Ste. Marie that the river level below the lake does not exceed elevation 582.9 feet (United States Senate, 1957, p. 15). Because of the rapids at Sault Ste. Marie, with a drop of about 20 feet in a mile-long reach, changes in the levels of Lake Michigan-Huron can have no effect on the outflow from Lake Superior or on its level (United State Senate, 1957, p. 25).

Outlet Conditions

The St. Clair River drains the water of the Lake Michigan-Huron basin into the lower Great Lakes. Increases in its cross-dimensional area would increase its carrying capacity and would therefore allow greater discharge from the basin than would occur otherwise. Natural erosion on the St. Clair River gravel and sand bed through the Port Huron rapids prior to 1900 was sufficient to cause a lowering of the Lake Huron level by .34 foot. "Such erosion was probably promoted by the dredging in Lake Huron, above, and in the St. Clair Flats, below. Shoaling caused by the wrecks of two schooners in the rapids in 1900 reduced this lowering to .24 foot" (Ramey, 1952 a, p. 28). Between 1908 and 1925 commercial dredging of gravel in the river enlarged the cross-dimensional area enough to lower the Lake Michigan-Huron level by an additional .29 foot (Great Lakes Basin Commission, 1972, p. 106; Ramey, 1952 a, p. 28).

The Joint Board of Engineers on the St. Lawrence Waterway Project (1926) estimated that the levels of Lake Michigan-Huron have been permanently lowered by approximately .6 foot since neither of the two influences have been compensated for by any type of river structure.

Navigational improvements in the St. Clair River completed in 1933 and 1962 further enlarged its discharge capacity. Korkigian (1963, p. 6) cites a figure of .13 foot at mean flow for the lowering of Lake Michigan-Huron water due to the 25-foot, 1933, channel improvement project. The Corps of Engineers (Great Lakes Basin Commission, 1972, p. 106) calculated that the construction of the navigational channels completed in 1933 and 1962 caused a total lowering of .59 foot in the levels of Lake Michigan-Huron.

In two papers Brunk (1963, 1961), a member of the U.S. Weather Bureau, noted that peaks were discernible in 10-year running averages of mean annual levels of the Great Lakes and Lake St. Clair in the 1880's and around 1950. The 1950 maximum was more than 1.5 feet lower than that of the 1880's. From studying Lake Erie water balance data he concluded that this drop in water level was attributed to downcutting of the channel connecting Lake Huron and Lake Erie. Water supply factors of precipitation, inflow, evaporation and diversion were not pertinent in this drop of water level. Lawhead (1961), of the Corps of Engineers, in a discussion of Brunk's 1961 article, claimed that the channel changes caused a lowering of the Lake Michigan-Huron level of only .73 foot between 1887 and 1955.

Combining the Corps of Engineers' estimate of the effects of dredging the 25-foot and the 27-foot channel in the 1930's and 1960's and the St. Lawrence Waterway report (Joint Board of Engineers, 1926) calculation prior to 1925, it can be inferred that the Michigan-Huron water level has been lowered approximately 1.19 feet from what it would be under "natural" conditions. This figure agrees somewhat better with Lawhead's figure than it does with Brunk's calculation. Perhaps Brunk's outcome was somewhat biased by the long-term above-average precipitation which played such a key factor in the high levels of the 1880's.

Effects of Diversions, Inflows and Outflows

The Long Lake-Ogoki diversion into Lake Superior and ultimately into Lake Michigan-Huron tends to cancel the outflow diversions at Chicago and through the Welland Canal. As of 1964 the effect that regulating Lake Superior by way of the St. Marys River system had on Lake Michigan-Huron levels was negligible (Great Lakes Basin Commission, 1972, p. 132). As previously mentioned, the St. Clair River channel modifications lowered the Michigan-Huron level by more than one foot, possibly one reason why the high levels of the 1950's did not approach the high levels recorded in the 1880's. One must remember, though, that the accumulated effect of all those years prior to the 1880's, when annual precipitation rates were always above average, may be a prime factor involved.

Groundwater Inflow and Seepage

The contribution of ground water to the water budget of Lake Michigan-Huron has not been determined but it is believed to be of insignificant proportion. Small amounts of water flow directly into the lake by subterranean movement, in addition to that which seeps into the stream channels and is included in the runoff.

SURFACE PRECIPITATION, LAKE LEVELS and UPPER AIR FLOW

The primary factor affecting the Lake Michigan-Huron water level is precipitation falling on its basin. During periods extending several years when precipitation rates are below normal the lake level will appreciably fall. The reverse will usually occur if the rates are above the mean during the extended period. An explanation of these long-term shifts in the precipitation pattern is complicated but would contribute to an understanding of natural fluctuations in lake levels. It is the purpose of this section to demonstrate that shifts in mean planetary wave positions occur between periods of contrasting precipitation rates; these shifts are apparently related to long-term variations in the level of Lake Michigan.

Mid-Latitude Upper Air Flow and Associated Surface Weather Conditions

The Great Lakes district lies in the westerly wind belt of the mid-latitude Northern Hemisphere. Here air masses migrating from contrasting thermal regions create a zone of baroclinity. The earth's rotation and air movement responding to this baroclinity generate a middle atmospheric west-to-east circumpolar wind flow. These upper level westerlies are rarely zonal, however, but assume a wave-like or sinuous plan (Figure 4). Two factors are responsible for this pattern (O'Connor, 1963; Harman, 1971). Vertical obstructions, such as mountain ranges, and land-sea thermal contrasts, particularly during the winter season, distort zonal flow and "force" an initial wave. This wave produces others (teleconnection) due to the tendency of the air to conserve its absolute vorticity (or spin); that is, "the

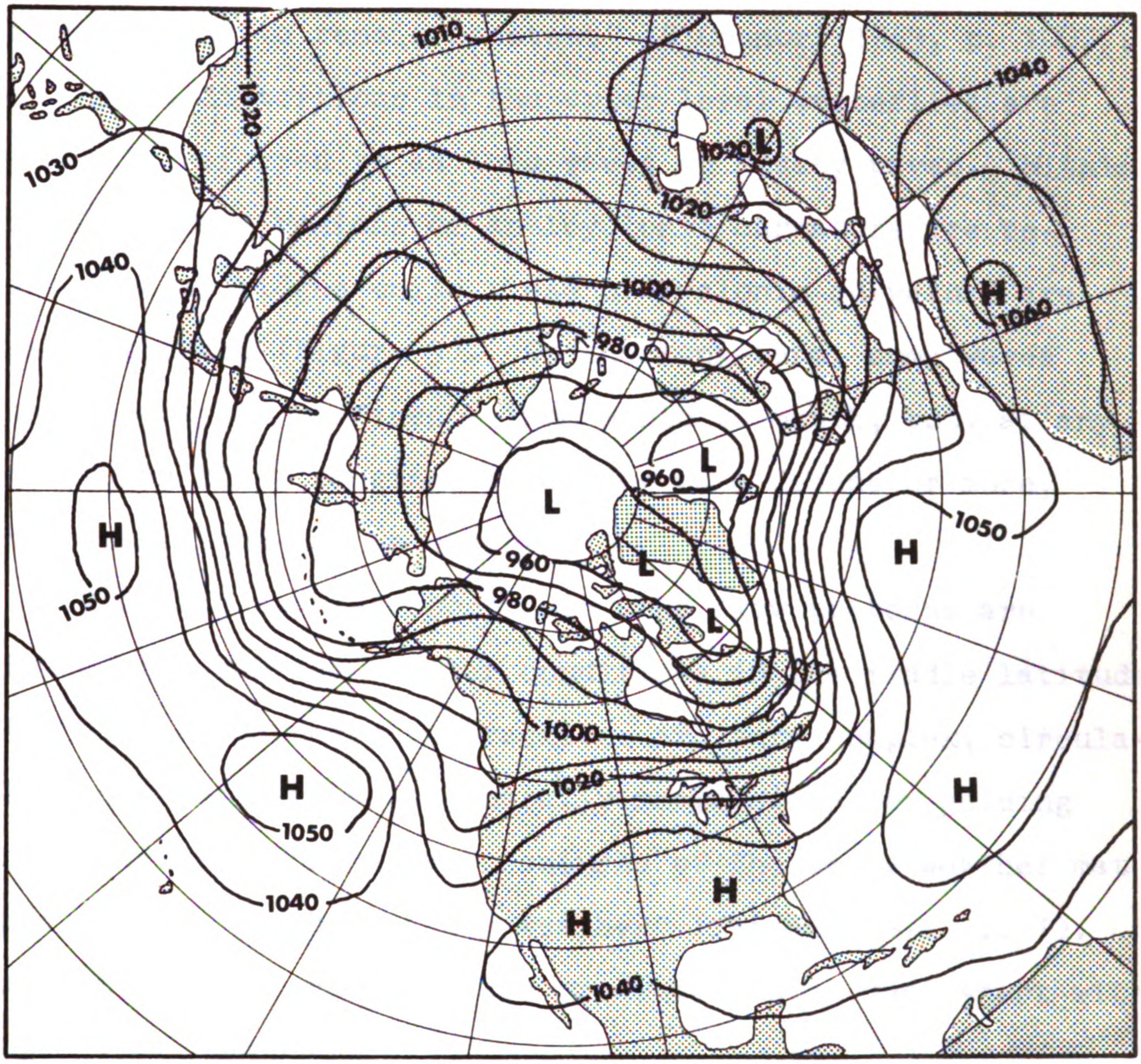

Figure 4: Mean 700 mb contours (tens of feet) for July, 1966, illustrating a typical mid-tropospheric summertime flow pattern. Note the trough along the U.S. west coast and a ridge over the northern Atlantic Ocean (adapted from Harman, J.R., 1971, p.21).

vorticity of the air stream, composed of the spin of the earth plus the curvature and the shear of the air motion, if any, tends to remain constant" (O'Connor, 1963, p. 1007).

These distortions in the upper level westerlies are generally referred to as long waves or Rossby waves. Within the air stream regions of anticyclonic curvature are referred to as ridges while those of cyclonic curvature are called troughs (Figure 5). On the long-term, some waves show geographic preference from month to month, but, at any particular time, ranging from a day to a decade or more, other positions may be observed.

Mid- and upper-tropospheric wind flow patterns are linked with surface weather conditions in the middle latitudes. "Although atmospheric interactions are very complex, circulation at these levels is generally responsible for guiding and generating the surface features of the daily weather map that produce our day to day weather" (Harman, 1971, p. 1). In fact, nearly every surface pressure center must start with upper level support.

Surface regions east of a trough axis, the region of positive vorticity advection, are characterized by surface air convergence, vertical uplift, and upper level divergence (Figure 5). The probability is high for precipitation associated with this area of uplift, and southwesterly winds tend to advect warmer air masses into the region. Clear surface weather predominates under the negative vorticity advection area to the rear of the trough axis. Here, upper

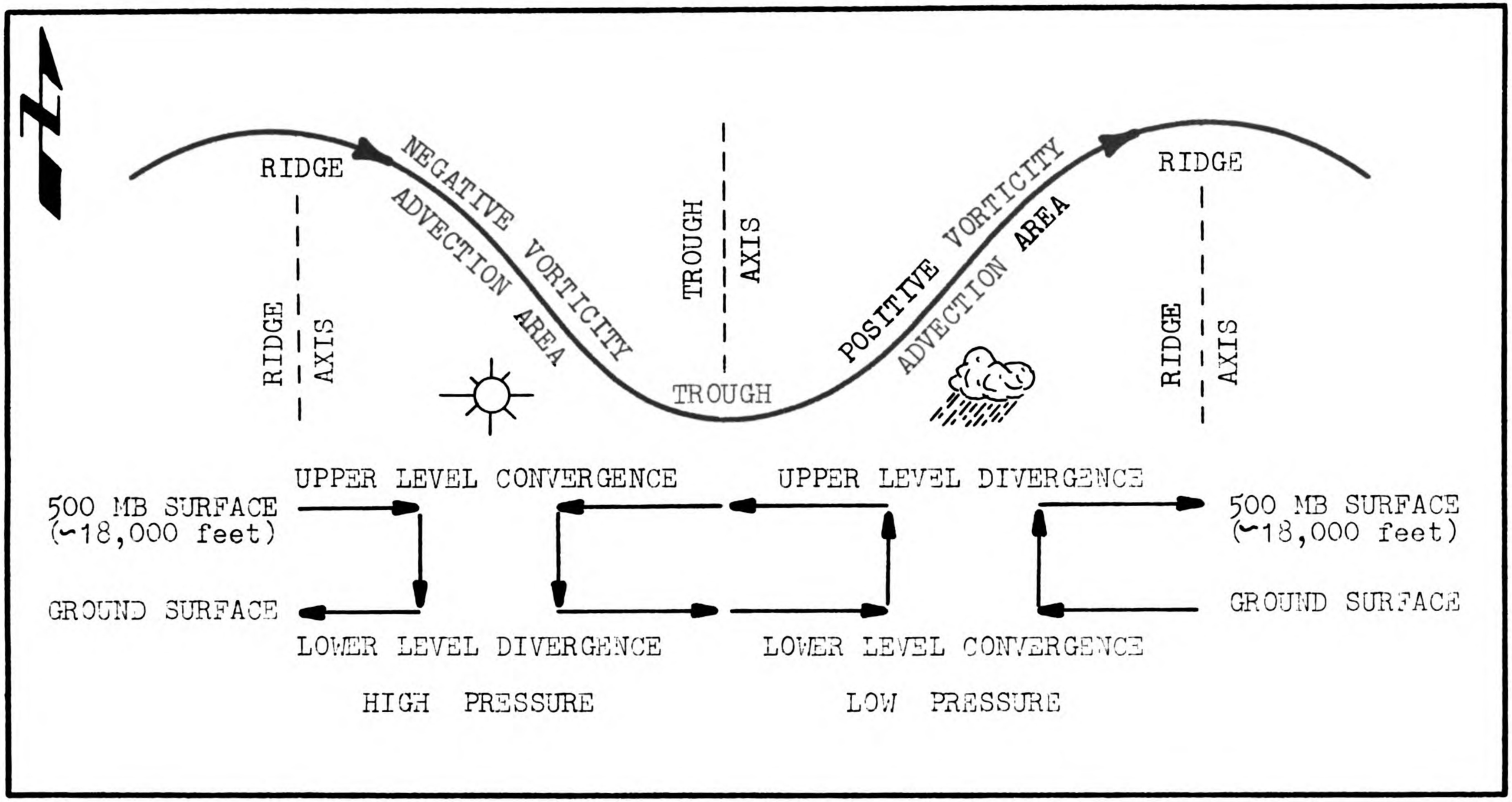

Figure 5: A schematic diagram of a tropospheric wave and associated vertical atmospheric motion.

level convergence, subsidence, and surface divergence occur, thereby fostering a high pressure region (Figure 5). Cooler air from higher latitudes tends to be advected into the area. Cyclonic tracks (Figure 6) show close spatial proximity to the former area while anticyclonic tracks display a positive spatial agreement with the latter region (Harman, 1971, p. 17; Klein, 1958, p. 102).

O'Connor (1963, p. 1007) suggests that "the abnormal longitudinal positioning of planetary waves (long waves) is one of the basic factors producing abnormal weather over large areas and long periods of time." Namias (1966) found that the 1962-1965 drought which plagued the Northeast (while the Southwest and Northern Plains simultaneously had a superabundance of precipitation) resulted from abnormal hemispheric wind patterns in layers of the atmosphere extending from the surface to the mid-troposphere, and probably much higher. Later, Namias (1969) concluded that abnormally high sea-surface temperature in the north-central Pacific Ocean between 1961 and 1967 was a primary factor in explaining a shifting of the upper waves from their modal (and mean) positions. This warm ocean temperature forced a southward winter-time displacement of the Aleutian Low. The developing and occluding cyclones associated with this system transferred their vorticity aloft, thus producing a change in the mean mid-tropospheric wind pattern. By teleconnection a strong mean ridge over the western United States accordingly was forced, while a strong mean trough resulted

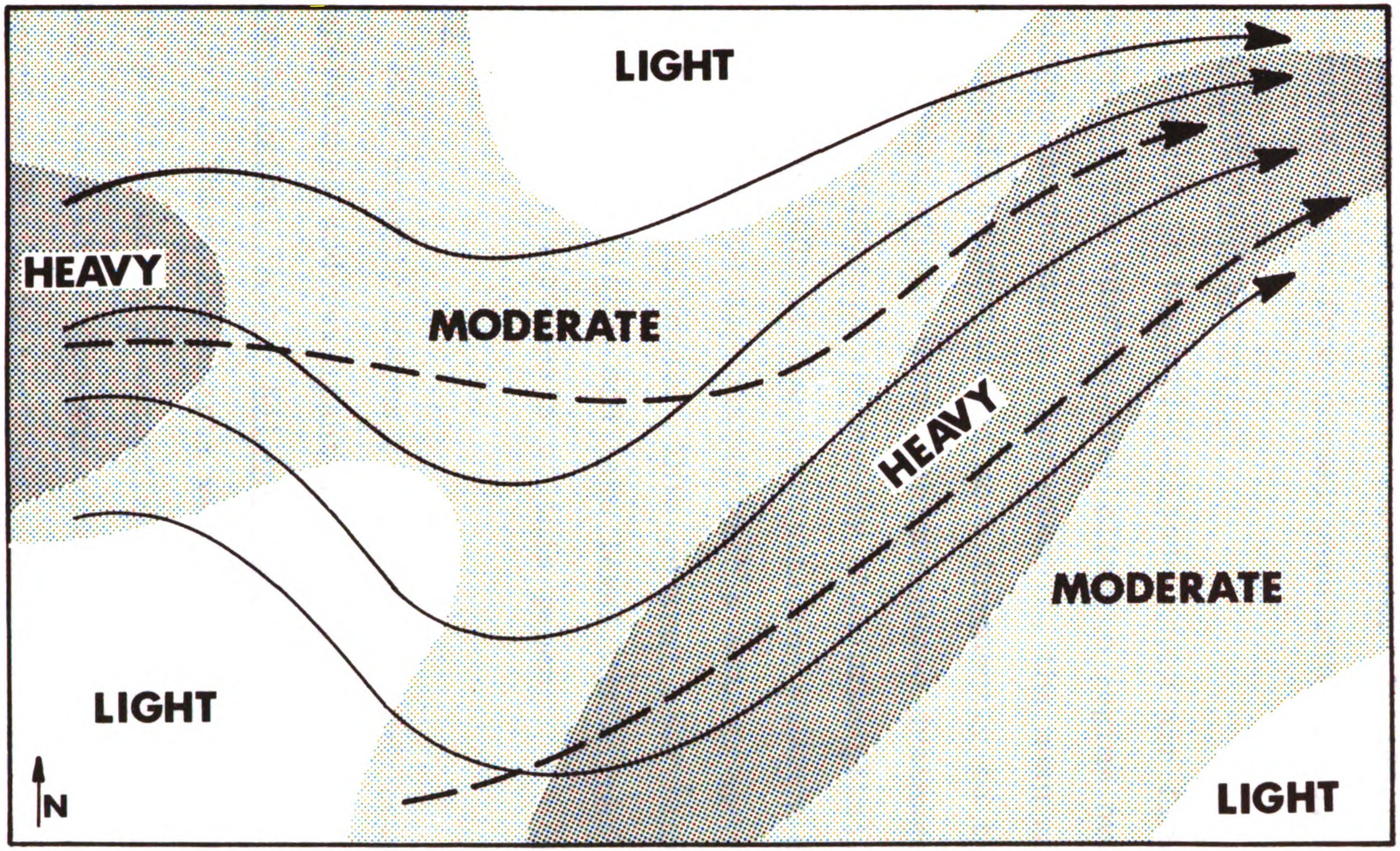

Figure 6: The relationship between precipitation and mean wind flow at the 500 mb surface. In this example the heavy dashed lines represent mean cyclonic tracks whereas the thin solid lines depict the planetary streamlines of flow over the United States during a hypothetical time period. Note that the heavy precipitation coincides with the southwesterly flow to the east of the trough axis (adapted from Harman, J.R., 1971, p.16).

over the eastern United States. Colder than normal temperatures occurred in the East and warmer than average temperatures persisted in the West. In addition, departures of precipitation from normal were widespread.

Investigative Hypothesis

Changes in the mid-latitude upper air flow should cause changes in the surface precipitation regime over the Lake Michigan-Huron basin. For example, the mean monthly trough axis should be positioned more frequently to the west than to the east of the Lake Michigan-Huron drainage area during extended periods of abnormally high precipitation and lake levels. Periods of low precipitation amounts and water levels should be associated with a mean trough axis east of the basin, in contrast. This general relationship between mean trough position and lake level variations formed the investigative hypothesis of this paper.

Data

Mean monthly charts of average 500 mb heights, temperatures and resultant winds were obtained from Climatological Data - National Summary for the period 1950 to 1971. These 264 charts were reproduced and trough axes were plotted on each according to the average height contours. Only those troughs whose associated wind flow crossed at least part of the Lake Michigan-Huron basin were considered.

Many important synoptic episodes of relatively short duration no doubt were undetected in this study because mean monthly wave positions often mask important intra-monthly variations. Nevertheless, mean monthly charts were used because of their availability and because it was assumed that important planetary wave patterns would still be evident.

Method

For each of the years, 1950 to 1971, each month was placed into one of three categories depending on whether the mean monthly trough was east (category "one"), west (category "two"), or directly over the study area (category "three"). Mean troughs west of the region typically produce southwesterly flow and abnormally frequent precipitation over the study area; dry subsident conditions prevail under a mean northwesterly flow when the trough axis is east of the region. Of the 264 months, eight displayed split flow patterns when part of the basin was under a mean southwesterly upper air flow while a mean northwesterly flow overlay the other portion of the drainage area. These eight months were placed in category "two."

Next, each of the 22 years was grouped into one of three time periods corresponding to episodes of above or below normal water level in Lake Michigan-Huron. High lake levels occurred between 1951 and 1955 and from 1969 to the present. Below normal water levels prevailed from 1956 until 1968 (Table 1). Due to the lag between basin precipitation and lake level fluctuations, these three study periods were offset one year in relation to the true water level periods. The 22 years were thus grouped into time spans to include 1950 to 1954, 1955 to 1967 and 1968 to 1971 (Table 4).

For 11 of the 22 years during the study period precipitation in the Lake Michigan-Huron drainage area was above normal. For the total of these years the average annual number of months in each of the circulation categories was determined. The same procedure was performed on the remaining 11 years during which time the annual precipitation amounts were below the mean (Table 5).

Discussion of the Findings

During the 11 years when basin precipitation totals were above normal the mean 500 mb trough axis was positioned west of the drainage area 1.55 months longer than during the 11 years when mean basin precipitation was below normal (Table 5). This finding implies that southwesterly flow and conditions favorable to general precipitation were more frequent than during the "dry" years and would seem to explain the long-term changes in precipitation. Hence, a correlation between long-wave positions and lake level fluctuations is evident even when monthly data are used.

The average number of months per year when the 500 mb trough axis overlay part of the basin was similar for both categories of high precipitation years and low precipitation years (1.91 and 1.82 respectively).

The mean monthly trough axis was located east of the Great Lakes basin an average of at least seven months each

Table 4: Departures from normal of the annual water level and precipitation amounts and the mean monthly 500 mb trough axis positions over the Lake Michigan-Huron basin, 1950-1971.

Year	Precipitation Departure From Normal (in inches)	Water Level Departure From Normal (in feet)	Number of Months When the Trough Axis Was to the EAST of the Basin	Number of Months When the Trough Axis Was to the WEST of the Basin	Number of Months When the Trough Axis OVERLAY Part of the Basin
1950	1.74	- .90	6	3	3
1951	6.06	.66	5	3	4
1952	-1.28	1.82	10	0	2
1953	-1.36	1.31	6	2	4
1954	5.48	.99	9	1	2
1955	-3.38	.62	10	1	1
1956	-2.77	- .30	10	0	2
1957	.99	- .82	6	5	1
1958	-5.81	-1.47	10	1	1
1959	5.59	-1.72	6	5	1
1960	1.76	- .20	10	1	1
1961	- .99	- .51	8	3	1
1962	-4.17	-1.03	12	0	0
1963	-5.84	-2.00	11	0	1
1964	-2.15	-2.82	7	3	2
1965	4.54	-2.05	10	1	1
1966	-2.08	-1.23	7	1	4
1967	3.03	- .79	8	2	2
1968	2.15	- .30	5	4	3
1969	.31	.53	10	2	0
1970	1.94	.45	5	4	3
1971	-1.29	.88	7	3	2

Table 5: The mean monthly 500 mb trough axis positions for the years when the annual precipitation amounts were above and below normal over the Lake Michigan-Huron basin, 1950-1971.

	Average Annual Number of Months When the Trough Axis Was to the EAST of the Basin	Average Annual Number of Months When the Trough Axis Was to the WEST of the Basin	Average Annual Number of Months When the Trough Axis OVERLAY Part of the Basin
Years When the Lake Michigan-Huron Precipitation Amounts Were ABOVE the Normal	7.27	2.82	1.91
Years When the Lake Michigan-Huron Precipitation Amounts Were BELOW the Normal	8.91	1.27	1.82

Table 6: The mean monthly 500 mb trough axis positions over the Lake Michigan-Huron basin for the extended periods of above normal water levels, 1950-1954 and 1968-1971, and below normal water levels, 1955-1967.

	Average Annual Number of Months When the Trough Axis Was to the EAST of the Basin	Average Annual Number of Months When the Trough Axis Was to the WEST of the Basin	Average Annual Number of Months When the Trough Axis OVERLAY Part of the Basin
1950 - 1954 (wet)	7.20	1.80	3.00
1955 - 1967 (dry)	8.84	1.77	1.38
1968 - 1971 (wet)	6.75	3.25	2.00

year for each of the two groups of years under consideration. The locational pattern resulting in these high yearly averages is typical of the mean North American flow, since a ridge is frequently "forced" over the Rocky Mountains, resulting in a mean trough over the eastern United States.

It should be expected that this relationship would hold true between extended, continuous periods of high water levels (and therefore high drainage area precipitation) and extended periods of lower lake levels (and therefore low basin precipitation). During the period 1955 to 1967 when the Lake Michigan-Huron level and the mean precipitation receipts were both low, the mean monthly trough axis was positioned east of the basin for over 1.5 months longer than during either period, 1950 to 1954 and 1968 to 1971, when water levels and precipitation rates were high. In the latter case, the mean annual difference was over two months (Table 6).

The trough axis was positioned to the west of the Lake Michigan-Huron basin for a yearly average of 1.8 months during the high water period 1950 to 1954. During the other extended period of high water, 1968 to 1971, the average was higher, 3.25 months per annum. This apparent discrepancy can be misleading. During the 1950-1954 period the trough axis had overlain the basin region for a month longer each year than during the 1968-1971 period, but was positioned west of the basin less frequently than during the latter. This fact suggests that the mean flow pattern was oriented in a position to increase the precipitation probability during both periods.

The mean 500 mb trough axis was positioned over the drainage area for an average of only 1.38 months per year during the low water period, 1955 to 1967. This mean was .44 months less per year than that calculated for the total years when the precipitation amounts were below normal (Table 5). Nevertheless, during the 1955 to 1967 interval the trough axis was found to be positioned to the west of the basin for an average of .5 months longer per year than during the 11 years when the precipitation amounts were below the norm (Table 5). Therefore, it seems that any effect which these extended position locations may have caused would have been negated by each other on an annual basis.

Conclusion

From this cursory examination there appears to be a definite contrast between upper wind flow patterns characteristic of periods of low and high lake levels in the Lake Michigan-Huron basin. During periods of high water levels the Lake Michigan-Huron basin appears to be under the influence of a mean southwesterly planetary wind flow considerably longer each year than during periods of low water levels. This mean southwesterly flow suggests a higher daily frequency of southwesterly flow patterns and attendant unstable weather. During abnormally low Michigan-Huron water levels northwesterly flow is more prevalent over the basin, this implying more frequent stable, dry anticyclonic conditions.

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APPENDIX

APPENDIX

NON-HYDROLOGICAL ELEMENTS AFFECTING THE LAKE MICHIGAN-HURON WATER LEVEL

In addition to long-term variations, seasonal and hourly variations in lake level occur within the Michigan-Huron basin. Seasonal and long-term variations result from change in the volume of water in the lake whereas daily and hourly variations arise from temporary shifts of the water within the lake basin, and are therefore non-hydrological in nature.

Daily and hourly changes in water level are local in nature and differ from place to place around the lake (Great Lakes Basin Commission, 1972, p. 99). Brief variations are caused by winds, shifts in barometric pressure, ice-blocked outlets and tides. Winds are by far the most important factor.

Crustal rebound, although long-term by its nature, is also a contributing non-hydrological factor affecting the Lake Michigan-Huron water level. It can hardly be thought of as a present-day threat to lake level stability, but in centuries to come, it could pose quite a problem.

Wind

Winds can produce temporary changes in lake levels. Frictional drag by the wind on the water surface can pile up water on the downwind side of the lake basin. This behavior of the water due to the wind is of utmost importance when a lake with a large surface area also possesses a shoreline zone which consists of unconsolidated and easily erodible material such as exists along the Lake Michigan basin boundary.

Wave heights are directly related to velocity, duration of the wind and the fetch (Brater, 1950, p. 13). The fetch refers to that open water distance over which the wind flows. For a given wind velocity the wave height tends to increase in the downwind direction until a maximum is reached. Due to its vast surface area, Lake Michigan provides a well-defined fetch for the westerly winds to travel over. Increase in wind velocity increases the potential wave height.

"The energy of a wave varies as the square of its height. Consequently, in a general way, it may be said that the power of a wave becomes four times as great when the wave height is doubled. It may be seen, therefore, that a knowledge of the frequency of occurence at various wave heights is essential in studying the erosion problem at any location" (Brater, 1950, pp. 12-13). Saville (1953 a) has utilized synoptic weather charts to predict past wave characteristics off of Milwaukee, Wisconsin, for a three year period. He also authored a Corps of Engineers Beach Erosion Board

Technical Mimeograph (1953 b) portraying wave characteristics along most portions of Lake Michigan.

Greater wave generation generally occurs on Lake Michigan during the fall and early winter. At this time the water temperature is characteristically warmer than the overlaying air masses. This situation creates an unstable air mass condition and tends to transfer momentum from the upper level gradient winds to the water surface (Strong and Bellaire, 1965; Strong, 1968). Spring conditions generally generate stable air conditions because the air masses are usually warmer than the water body.

Ramey (1952, p. 24) cites several examples. In October, 1929, a continuous strong north wind raised the Lake Michigan level 1.95 feet at Chicago in 37 hours. In November, 1951, an east wind, shifting to a strong 42 mph northerly wind raised the water level at Chicago by 1.70 feet. As this wind subsided over the next 24 hours to nine mph the level dropped 1.10 feet. As it shifted to a southerly wind and increased its velocity to 23 mph, the Lake Michigan level dropped an additional .8 foot.

Barometric Pressure Changes

Harris (1953, p. 26) noted that short period disturbances in the Great Lakes tended "to occur in zones of disturbed weather, that is, near fronts, squall-lines, thunderstorms, etc . . ." In June, 1954, an abrupt 10 foot surge in the Lake Michigan water level inundated the Chicago shoreline shortly after a storm system had passed. In an article in Science Ewing, Press and Donn (1954) noted that a few hours earlier a severe squall line with winds up to 60 mph had arrived from the northwest and had crossed southern Lake Michigan. Associated with this squall was a very rapid and strong pressure jump. They suggested that this disturbance could be explained "on the basis on resonant transfer of energy from the traveling pressure-jump and its associated high winds in the air to a gravity wave traveling with equal velocity in the lake. Only for equal velocities can a large wave be generated" (p. 685).

Harris (1957) expounded on this theory in relation to the 1954 Chicago surge and arrived at the conclusion that "in determining which pressure jump will be accompanied by important water level disturbances in Chicago, it is likely that the orientation of the pressure jump will be equally or more important than the speed of the disturbance. This is because shoaling, reflection, and convergence due to the contours of the shore must all be considered to account for a disturbance of the observed magnitude" (p. 56).

Minor changes in water levels are probably common to most all migrating pressure cells but significant surges are relatively uncommon. When they occur their consequences can be dramatic. The Monthly Weather Review, in a three part study (Platzman, 1965; Irish, 1965; Hughes, 1965), presented papers concerned with the type of atmosphere-lake interaction which occurred at Chicago. Hughes (1965) describes other water level surges which have taken place on Lake Michigan.

Differences in atmospheric pressure at opposite ends of a lake can have much the same effect on water levels as that of a steady wind blowing from one end to the other. If a high pressure cell overlies one end of the lake for a period of time, while a low pressure system overlies the other end, the high pressure cell has a depressing effect on the water. This must be compensated for by an increase in water level elsewhere where atmospheric pressure is less. Consequently, discrepancies between levels at one end of the lake and the other may be several feet.

The combined effect of wind and barometric pressure changes which occur in certain storm systems has a magnifying quality. Incoming high pressure cells tend to depress the water level at one end of the lake while downwind the water level increases beneath the low pressure cell. This increase in water level is amplified by the fact that the wind is also increasing the level in the downwind direction. In addition to this, the large waves generated by the wind during the storm have the capability of surging still further up the beach zone. It can be seen, then, that the elevation of a steady-state water level can be temporarily increased to a great extent by combined changes in barometric pressure and wind flow. If this condition occurs during periods of above average water levels severe consequences may result along the erodible shoreline. In one study (Fox and Davis, 1970), analysis of 17 environmental parameters recorded during a storm revealed positive relationships between shoreline erosion and barometric pressure, wind, breaker height, breaker angle and longshore current along the southeastern shoreline of Lake Michigan.

Seiches

Short-time standing wave oscillations in the surface of the lake may result from changes in atmospheric pressure and wind direction. Such oscillatory waves are called seiches and on Lake Michigan are reported to have caused local changes in water levels as great as five feet (Dorr and Eschman, 1970, p. 224). "The initial impulse which starts a seiche in the Great Lakes is probably much more frequently due to the wind than to barometric gradient" (Hough, 1958, pp. 44-45).

It is interesting to note that seiches were recognized to have occurred "due to large and rapid atmospheric changes noticeable upon the barograph preceding or during thunderstorms" as early as 1899 (Mansfield, 1899, p. 42). Mansfield describes a particularly violent one on Lake Michigan which occurred in 1893 at Chicago. Water suddenly had risen four to six feet in a series of heavy waves.

Ice Retardation

Ice jamming of the St. Clair River during the winter reduces outflow from the Lake Michigan-Huron basin. The result is a lowering of the Lake St. Clair and Lake Erie water levels while the level of Lake Michigan-Huron is increased because of the restricted flow. In some winters the discharge of the St. Clair and Detroit Rivers has been reduced by as much as one half for a monthly period of ice obstruction; in other winters there has been little retention of outflow by ice (Freeman, 1926, p. 207). The Great Lakes Basin Commission's draft report (1972, p. 84) cites a 1965 Corps of Engineers study which estimated that the level of Lake Michigan-Huron is about .4 foot higher than it would be without ice retardation.

Tides

Both lunar and solar tides exist on Lake Michigan but their effect is so small as to be inconsequential. The National Ocean Survey, Department of Commerce (formerly the U. S. Coast and Geodetic Survey) has determined that the spring tide (combined lunar and solar tides) is less than two inches (Ramey, 1952, p. 24). This is masked by the greater fluctuation in levels produced by wind and barometric conditions.

Crustal Rebound

In the 1890's G. K. Gilbert astutely perceived that late- and post-glacial isostatic adjustment of the earth's crust following glacial unloading had occurred and was presently taking place in the Great Lakes region. The earth's surface, previously depressed under the ice of continental glaciation, had begun to warp slowly upward once the ice thinned and retreated. This crustal uplift is not uniform in all areas. In the Lake Michigan district a hinge line extends in a northwest-southeast direction between the south tip of Green Bay to approximately the latitude of Manistee, Michigan. North and east of this line the crust is still rebounding.

At one time the upper Great Lakes drained northward through northern Ontario, but, due to the isostatic adjustment of the earth's crust, the drainage is now south and east through the St. Lawrence system.

As time passes the differential crustal uplift of Lake Michigan's northeastern rim may tilt the water enough relative to its southwestern rim so that the lake may naturally drain across the divide at Chicago into the Mississippi basin. Freeman (1926) suggested that this may become a serious problem in a thousand years.

As should be evident, then, water levels along the shore at localities north and east of the hinge line are receding with respect to the water level at the Lake Huron outlet and at Chicago.