CHAPTER 209

TWO TREATMENTS OF SHORE EROSION IN EXTREME FLOODS ON U.S. GREAT LAKES

Robert J. Hallermeier[1]

Abstract

This investigation addresses empirical evidence on wave action and shore erosion during extreme floods on Great Lakes coasts. Historical information shows that record coastal floods on the Great Lakes usually involve moderately extreme storms during relatively brief intervals with overall lake level much above the long-term average. The 100-year flood on U.S. lakeshores appears most likely to be accompanied by coastal wave heights with recurrence interval of about: three years on the four upper Great Lakes; or one-half year on Lake Ontario. Shore changes during the 100-year flood seem susceptible only to a coarse statistical estimate because available studies reveal Great Lakes erosion to be extremely variable in onset and amount. Two simplified erosion treatments are outlined here, one applying average annual recession rate for a locality, and the second, an empirical relationship originally developed for seacoast storm effects. The latter treatment appears verified by evidence from a Lake Michigan study, and such estimates of episodic erosion cross section are much lower than for extreme events on U.S. seacoasts.

INTRODUCTION

Conclusions developed in the following material are intended for application in the U.S. National Flood Insurance Program (NFIP). The NFIP includes the generation of maps quantifying expected hazards for the local base flood, an event having average annual probability of one percent (or mean recurrence interval of 100 years). Suitable coastal assessments must take into account distinctive characteristics of extreme events along Great Lakes shores, reflecting the particular basin configurations along with the marked variations of mean water levels over long terms.

To demonstrate the distinctive circumstances on the Great Lakes, Figure 1 displays annual mean water levels since 1860 for Lake Huron, with very large oscillations apparent but no clear trend during this century. That behavior strongly differs from the historical sea levels on the Atlantic ocean, where a rising trend is the most notable feature and other variations appear relatively minor. These signals indicate a

[1] Senior Coastal Scientist, METS Division, Dewberry & Davis, 8401 Arlington Boulevard, Fairfax, Virginia 22031-4666, U.S.A.

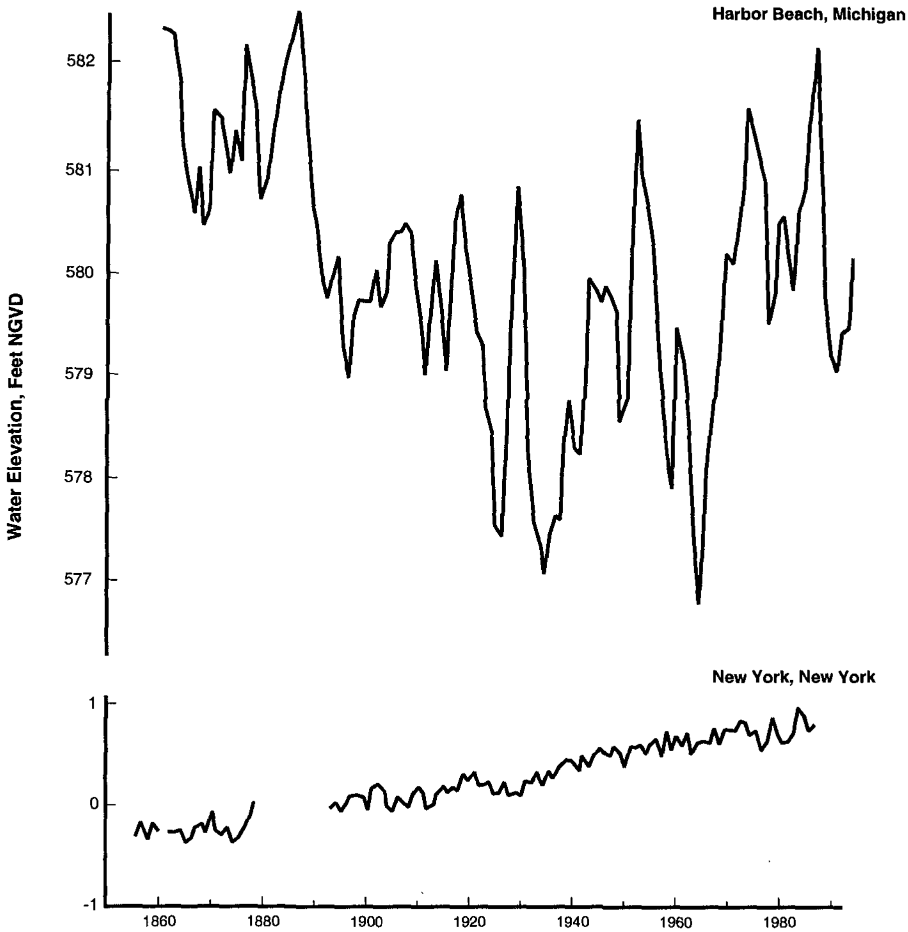

Figure 1. Annual mean water elevations on Lake Huron and Atlantic seacoast

markedly different context exists for coastal processes and extreme floods on the Great Lakes, in comparison to seacoasts.

Until recently, only stillwater inundation was considered in mapping coastal flood hazards for the Great Lakes, but documented flooding during the 1985-1987 highs clearly established the importance of additional wave effects. For NFIP treatments of U.S. Great Lakes shores, a full suite of methodologies for hazard assessment now addresses local stillwater flood elevations, shore erosion expected during the base flood, wave dimensions including growth or decay in coastal areas, and wave runup elevations at barriers to flooding. The U.S. Army Corps of Engineers (USACE) has documented conclusions on extreme local stillwater elevations from long-term records (USACE, 1988) and has provided a simplified treatment for wave runup at the most common types of shore barrier (USACE, 1989). This paper outlines the development of guidance on two other aspects of flood hazards: incident wave action

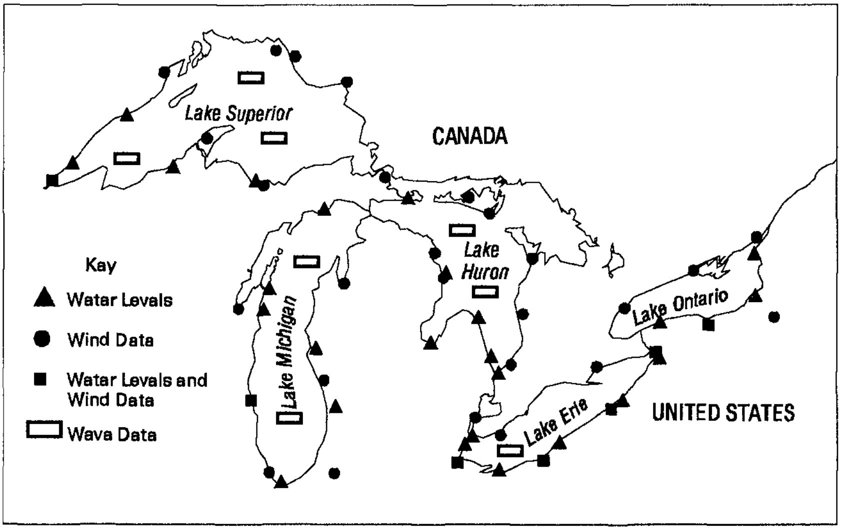

Figure 2. Pertinent data locations for Great Lakes investigations

and resultant shore erosion expected to accompany a base flood on the Great Lakes. These topics are interrelated, since shore erosion from wave action with flood waters alters the crucial boundary condition for storm impacts, thus controlling magnitude and penetration of wave effects over flooded land.

The following considerations are entirely empirical in basis, using best available information on recent extreme events. Quantitative analyses (Dewberry & Davis, 1995) have examined storm wave heights, flood elevations, and erosion magnitudes documented at about 100 varied sites on the U.S. Great Lakes. The necessary order of treatment begins with wave conditions during floods and proceeds to erosion considerations.

WAVE ACTION DURING FLOODS

Wave conditions during record Great Lakes floods have been computed in the recent USACE hindcast covering 1956 to 1987 (e.g., Hubertz and others, 1991). That interval includes 20th-century highs in mean lake levels during 1973-1975 and 1985-1987, along with record instantaneous elevations at many water-level gauges. Before combining this disparate information on waves and water levels for extreme events at particular sites, it is appropriate to examine the reliability of wave hindcast results. Figure 2 provides a map locating important data sites.

The USACE hindcast procedure applies measured winds at scattered land stations (Figure 2) to define wind fields over each lake, and then computes resultant wave action at many deep-water sites. Validation possibilities for hindcast computations are restricted to limited nearshore measurements and to several long-term buoy sites near the lake centers (Figure 2). The reported verifications of hindcast waves tend to

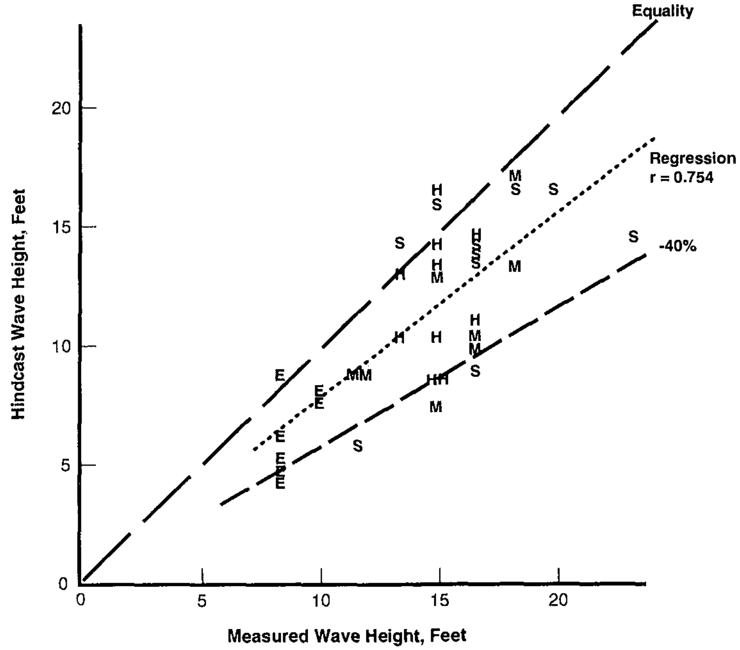

Figure 3. Hindcast versus measured extreme wave heights on four upper Great Lakes; separate lakes identified by initials used in plot.

focus on overall distributions of parameters, consistent with a comprehensive long-term hindcast. However, the present application utilizes brief intervals of storm winds, surges and waves, so the hindcast reliability for such extreme conditions merits evaluation. This is in line with the caveat stated by Hubertz and others (1991): "It is recommended that separate studies be done for specific storms at specific sites for more detailed information."

A convenient evaluation of the hindcast may be based on 35 extreme wave heights tabulated in a published summary of buoy data (Gilhousen and others, 1991). Those 1979-1987 measurements pertain to eight buoy sites on the four upper Great Lakes, and include all tabulated wave heights among the extreme 1% at each site. Hindcast wave height for each case is taken as the highest value during the same wind episode at a nearby computation point. This present selection yields a fairly balanced sample of extreme conditions, with separate lakes identified by the initial used in plotting results on Figure 3. Measured wave heights in this sample are typically on the order of 4.5 m (or 15 feet). Comparison of hindcast and measured wave heights yields a correlation coefficient sufficient to confirm a linear relationship with certainty. However, the hindcast does not accurately reproduce these measured conditions, being 20% low typically and having an error band of ±20%. Part of the hindcast bias may be explained by a lower peak value with the three-hour hindcast interval versus hourly measurements, but the error band remains notable. That sizable random scatter of hindcast wave heights appears related to errors in interpolated winds at buoy sites, as shown in Figure 4 using measured windspeeds also tabulated for a typical 7 of the 35 cases (Gilhousen and others, 1991).

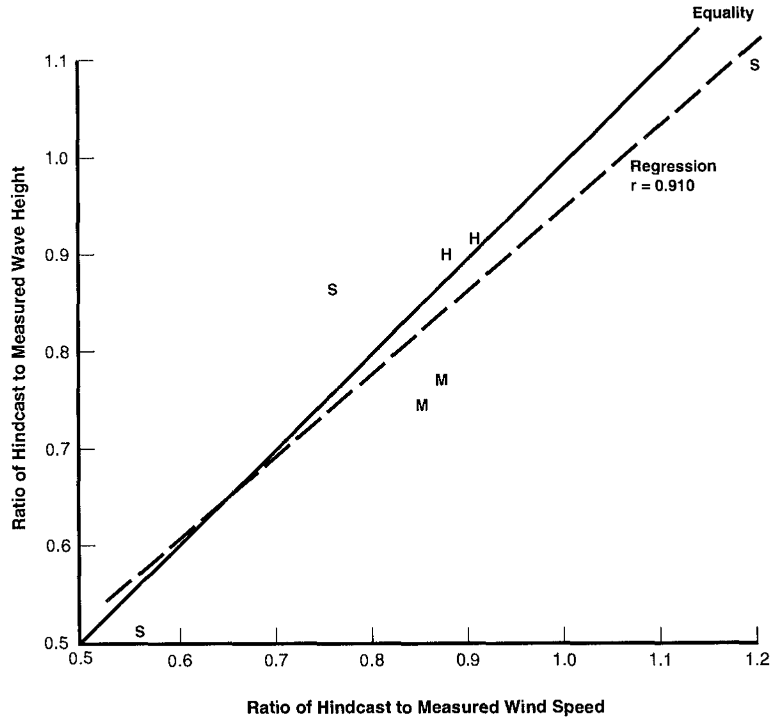

Figure 4. Relation of wave height and windspeed errors in Great Lakes hindcast.

According to this modest but objective selection of storm events, there are considerable errors in the USACE hindcast of extreme wave conditions on the Great Lakes. The data buoy sites may present a notable challenge for wave hindcasts, given relatively large separations from wind data locations. Hindcast results may generally be more reliable at nearshore sites, but appreciable variations in accuracy still seem likely in view of the scattered stations providing wind data. To apply USACE hindcast information in assessing wave action accompanying extreme floods, it seems advisable to maximize the variety of sites and events considered together, aiming at a simplified conclusion with generic pertinence to Great Lakes shores.

That program is carried out by considering in one group the record flood during 1956-1987 at each of 32 water-level gauges (Figure 2), along with wave hindcast results at a nearby computation point for the same episode. To use evident measures of extremity, both peak measured water elevation and largest computed wave height for each event are converted into recurrence intervals from the type of results shown in semi-logarithmic form on Figure 5. There, purely exponential recurrence relations as straight lines are fully defined by the medians of monthly and yearly highs, plotted at recurrence intervals of two months and two years, respectively. Such simplified analysis provides the advantages of a direct basis in annual probability along with a recurrence estimate for any value; note that results for relatively common flood elevations relate smoothly on Figure 5 to reported USACE conclusions on extremes. This example of recurrence relations is remarkable because each line has nearly

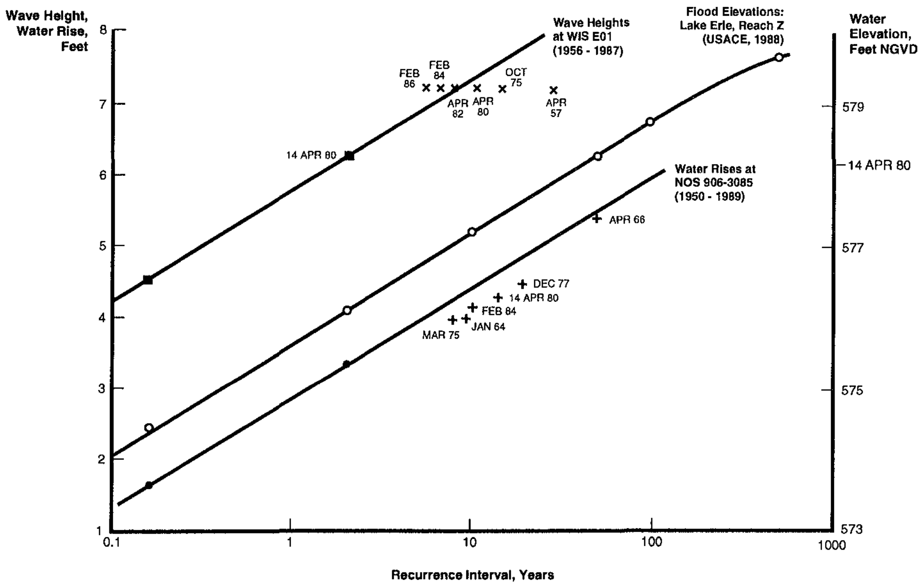

Figure 5. Summaries of extreme effects on Lake Erie at Toledo, Ohio

identical inclination. The inclination is representative of flood elevations on any of the Great Lakes except Lake Superior, where the line would tilt much less; for wave heights, the line has about the minimum inclination to be found on the Great Lakes, while water rises typically define a line with less inclination.

Figure 6 presents a logarithmic cross-plot of recurrence measures for the 32 extreme events, again distinguishing the separate Great Lakes by initial. Measured flood elevations for these cases typically have recurrence intervals on the order of 50 to 100 years. Immense scatter is evident among these results, in part reflecting the notable errors possible in hindcast wave heights and those recurrence intervals. The ± 20% estimate based on Figure 3 converts to various sizable ranges in recurrence intervals for wave heights here, depending strongly on the hindcast result and the local recurrence relation; a usual error bar for representative results extends over a factor of ten. However, a very wide range in wave extremity certainly can be associated with a given flood elevation on the Great Lakes, considering that significant variables include mean lake level and lake seiches, in addition to storm winds.

From close inspection of available evidence, floods on Lake Ontario differ from effects on the four upper lakes in always being associated with very common hindcast wave conditions; in contrast, notably extreme waves occasionally occur during many floods on the other Great Lakes. Deleting the Lake Ontario floods in Figure 6, remaining results yield a sizable positive correlation between recurrence intervals for wave height and flood elevation. The regression result shown in Figure 6 has statistical significance at the 5% level (but not the 1% level; Sachs, 1984), and indicates wave height recurrence of about 1 year for the 100-year or base flood. Since the correlation has limited significance, this evidence may also be examined

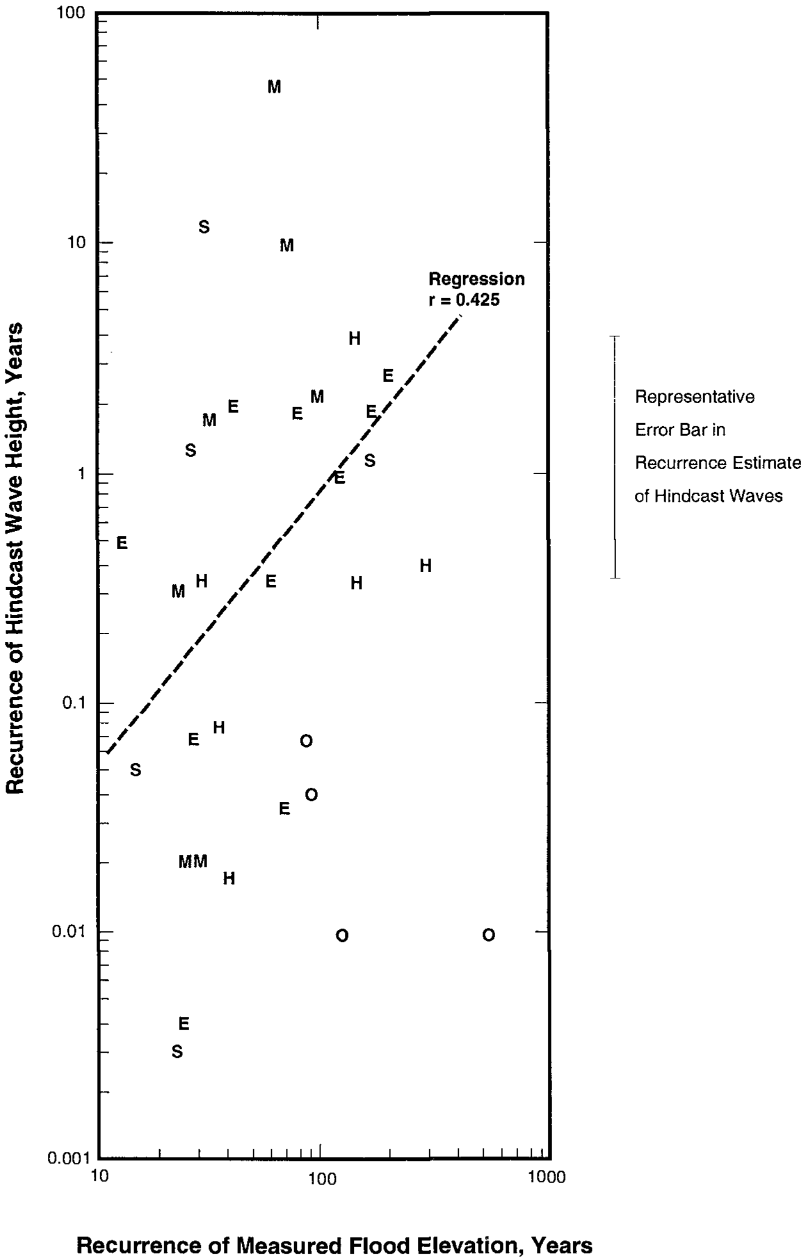

Figure 6. Parameters describing 32 recent extreme floods on Great Lakes; displayed regression result omits events on Lake Ontario (O).

without regard to trend: the most common condition with these record floods is about a 2-year wave height, according to the band of results in that vicinity. Such wave conditions occur during events from mid-November through mid-April, when storm winds can overwhelm the seasonal water levels least conducive to flooding. Taking into account the hindcast bias, these considerations indicate a prudent conclusion to be that a 3-year wave condition (as defined here by an exponential recurrence relation) accompanies the base flood at typical U.S. shore sites on Lake Erie, Huron, Michigan, or Superior.

Hourly water-level measurements demonstrate that lake seiches rather than storm surges are dominant in extreme flood elevations on the U.S. shore of Lake Ontario. There, the large seasonal excursion of mean lake level enhances flooding during the usual May-July high, when onshore storm winds rarely occur. An appropriate conclusion is found to be that wave height with a ½-year recurrence interval accompanies the base flood on U.S. shores of Lake Ontario.

Present conclusions must be recognized as highly generic regarding the likely wave action during extreme floods on the Great Lakes, and as somewhat tailored for routine NFIP application. Additional analysis or historical evidence may provide more appropriate estimates for specific shore sites.

EROSION EFFECTS AND TREATMENTS

Detailed measurements of shore changes pinpoint the apparent complexity of Great Lakes effects over space and time. A striking attribute is erosion variability over all but the longest terms, so that coastal changes during extreme conditions seem coherent only in a statistical sense over appreciable shore reaches. Many factors can be important in Great Lakes erosion processes, but the characteristic result appears to be quite intermittent progress in the fall and removal of dune or bluff sediments, yielding a markedly slowed or interrupted replica of typical seacoast storm effects. This discussion will address just a few erosion studies on sandy coasts of Lake Michigan, considered representative for various erodible lakeshores.

Two intensive studies, Hands (1979) and Birkemeier (1981), documented erosion along the eastern shore of Lake Michigan during the 1964-1973 interval when the increase in mean lake level was about 1.5 meters. Hands (1979) reported shoreline positions at irregular time intervals of a year or more, for a total of 30 transects spanning about 50 km near Pentwater, Michigan. Alongshore variability of retreat rate was extreme as lake level generally rose over 8 years, but the average or median rates over available transects were rather steady in time, regardless of mean lake level or storm climate variations. Those findings do not appear sensitive to the spatial or temporal frequency of measurements, or a later study area extension. As lake level declined over the last study year, shore accretion typically reversed about two years of retreat. The basic results might be summarized as indicating a lagging response to the increasing erosive stress with rising water, but only in an overall sense; changes on individual transects appear too variable in time for simple interpretation.

In the other study, Birkemeier (1981) summarized survey results at four-week intervals during 1970-1974, for 17 profiles roughly 20 km apart. Shore erosion appeared somewhat random in time and location: various numbers of profiles showed bluff or terrace retreat in greatly varying amounts over separate intervals. However, erosion was also clearly seasonal, in phase with the annual storm cycle but not with

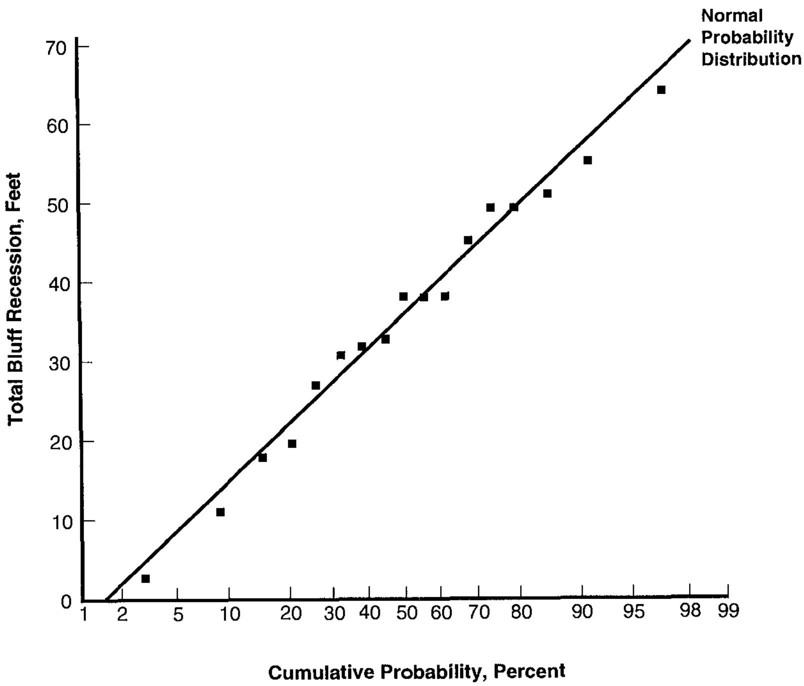

Figure 7. Bluff recessions during 1970-1974 on 17 Lake Michigan profiles.

the lake level cycle. Through the complete study term, changes accruing through sporadic episodes disclose some orderly variation over the entire data set: total recessions on individual profiles conform to a normal probability distribution with sizable dispersion, as shown in Figure 7. With no clear geographical trends, nor much correlation between adjacent profiles, the effectively random scatter of recorded erosion seems to result from the interplay of many independent factors, with insufficient time to develop an equilibrium response.

Even long-term changes on the Great Lakes can require careful interpretation due to the dependence of shore erosion on mean lake level, as revealed by results from two recent studies of Lake County, Illinois. Jibson and others (1994) addressed rates and processes of bluff erosion based on measurements for 1872-1937 and 1937-1987. Average retreat rate over the region showed no significant difference for the two periods, during which mean lake level or precipitation was nearly identical. However, Chrzastowski and others (1993) studied the same shore reach and timespan, but with three intervals isolating sizable elevation differences for Lake Michigan. Documented results reveal significant correlations between the mean lake level and representative movements of sandy shoreline or coastal bluff top, as demonstrated in Figure 8. Since differences from the long-term mean can be larger over briefer intervals, mean lake levels apparently contribute to sizable departures from an average erosion rate.

With this brief outline of factors and variabilities in Great Lakes erosion, it seems clear that statistical viewpoints can most conveniently provide useful summaries or projections. In turn, projections for short-term or storm erosion may be expected to

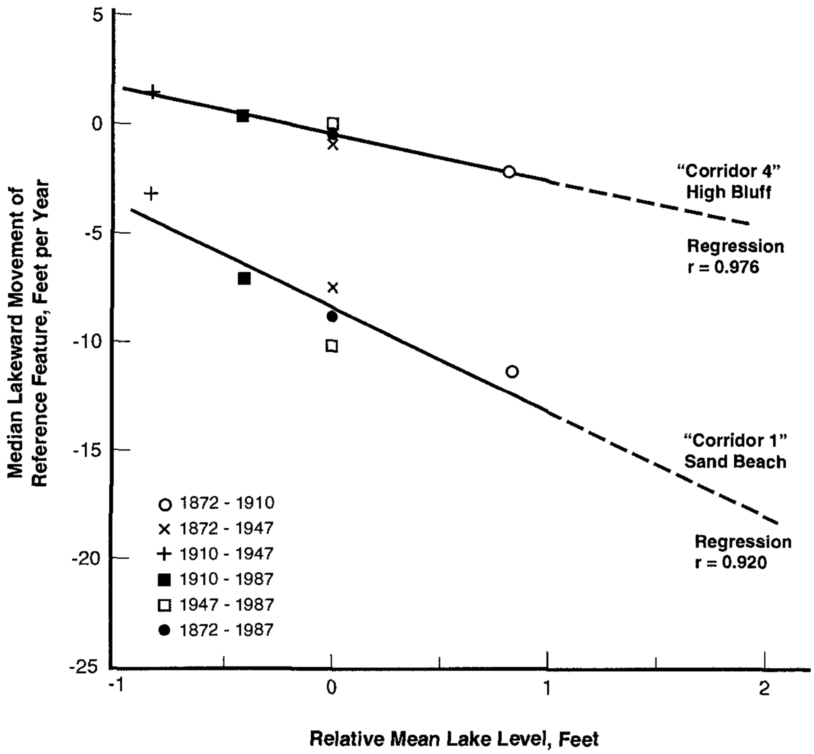

Figure 8. Representative erosion rates versus mean Lake Michigan levels.

attain only order-of-magnitude agreement with actual effects, but suitable procedures for erosion estimates might be rather simplified or generalized in basic character. Two treatments outlined here apply either average local recession rate, or storm erosion quantities from a generic database, the two evident alternatives. The independent treatments take into account distinctive attributes of the Great Lakes.

The first alternative applies the local value of A, average annual rate of shore recession over a long term. This development presumes available topography to be defined during usual lake levels, and addresses cumulative erosion until the base flood is likely to be encountered. As mean lake level rises to highs conducive for the base flood, shore recession is more rapid than the long-term average, and described as a rate of (2.5 A). If that rate occurs over about one-third of a long term, it implies that (0.25 A) is characteristic otherwise, and such a range of values appears appropriate according to available Great Lakes studies. Projected erosion before the base flood equals the accelerated rate times an expected waiting time of 4.8 years with high lake levels. That waiting time is supported by the normal probability distribution defined by data in Figure 9: actual intervals of high lake level before the record flood during 1972-1987, at 31 gauges on the four upper lakes. Given the notable storm waves likely to accompany an extreme flood on the four upper lakes, the additional allowance of (3A) for storm erosion in the base flood appears appropriate. These considerations yield (15A) as projected site erosion on Lake Erie, Huron, Michigan,

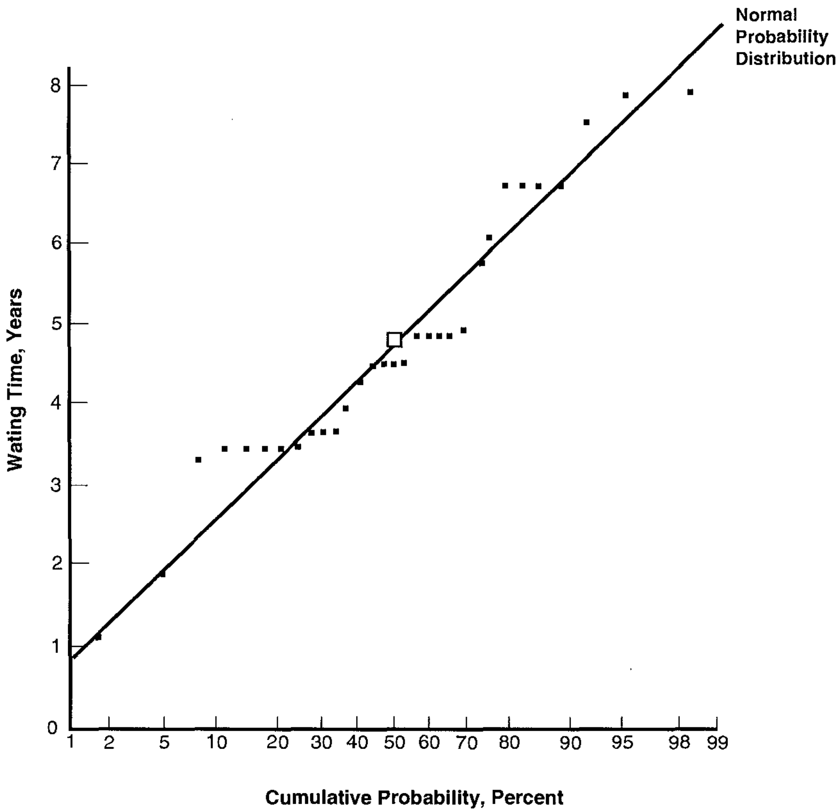

Figure 9. Waiting times for record floods at 31 sites on four upper Great Lakes, after onset of monthly mean levels higher than long-term mean.

or Superior; and (12A) on Lake Ontario. These recession distances describe a parallel retreat of the shore profile from the reference feature to which A pertains.

Such treatment seems relatively straightforward, but the result does not appear validated by measured Lake Michigan erosion reported by Birkemeier (1981). On 17 profiles in nine separate Michigan counties, total recessions over 4.3 years of high lake level show essentially no correlation with average long-term recession rates documented for the individual counties. Although no extreme flood occurred within the study area over this term, cumulative recessions make the present estimation method seem of dubious usefulness. This might be caused by the multiplication of two very uncertain quantities, in regard to short-term applicability at specific sites.

The second alternative considers only the storm effects likely to be associated with the base flood, using an empirical relationship for expected erosion in duneface retreat on U.S. Atlantic and Gulf coasts (Hallermeier and Rhodes, 1988). The relationship expresses eroded cross section above flood elevation in terms of recurrence interval for the flood, amounting to 50 m^2 erosion in a 100-year event:

$$\text{Erosion } [m^2] = 8 \text{ (Recurrence Interval [yr])}^{0.4} \tag{1}$$

This erosion treatment has proved to be suitable for NFIP applications in defining coastal flood hazards, and has been validated by effects recorded in more recent extreme events (e.g., Wolf and others, 1993).

Along U.S. seacoasts, wave condition and flood elevation generally may be expected to have comparable recurrence intervals for most episodes in a sizable sample of extreme events, but that is not the case for the base flood on the Great Lakes, as established by Figure 6. This application therefore employs a blend of individual erosion estimates for the wave and flood recurrences, using the geometric mean of cross sections defined by the basic relationship in Equation (1). Resultant erosion for the base flood, with a ½-year wave condition on Lake Ontario and a 3-year wave condition on the four upper lakes, is estimated as: 17 m^2 for Lake Ontario sites; and 25 m^2 on Lake Erie, Huron, Michigan, or Superior. These quantities are taken to be eroded amounts above local 100-year stillwater elevation.

Results from this erosion treatment appear consistent with storm erosion quantities documented in the Lake Michigan study by Birkemeier (1981). Erosion was recorded on a majority of the 17 profiles only during two intervals, covering notable storms in mid-December 1971 and in mid-March 1973. As defined by USACE hindcast wave heights and measured water elevations: the 1971 storm had ½-year waves and a 1-year flood, giving an erosion estimate of 7 m^2; and the 1973 storm combined 4-year waves and a 1½-year flood, for an erosion estimate of 11 m^2. Average bluff cross sections removed on the eroding profiles in those events were 8 m^2 during December 1971 (for 10 profiles) and 10½ m^2 during March 1973 (11 profiles). The quantitative agreement of estimates with representative erosion magnitudes in these cases provides appreciable validation of the present viewpoint, since base flood estimates for the Great Lakes lie between these amounts and many documented seacoast episodes. However, serious uncertainties in predicting the onset and amount of short-term erosion at Great Lakes sites remain worth emphasizing.

CONCLUSIONS

Empirical evidence provides an extensive basis for simplified summaries of the wave action and erosion expected to accompany the base flood on U.S. shores. Lake Ontario sites may be expected to experience wave heights having recurrence interval of ½ year and eroded cross section of 17 m^2 above flood elevation. Wave heights having recurrence interval of 3 years and erosion of 25 m^2 are projected for sites on Lake Erie, Huron, Michigan, or Superior. These results pertain only to storm-induced flood episodes, and are intended for routine application in flood hazard assessments within the National Flood Insurance Program.

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