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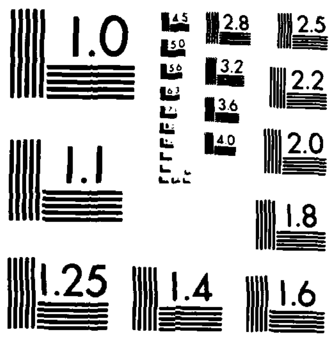

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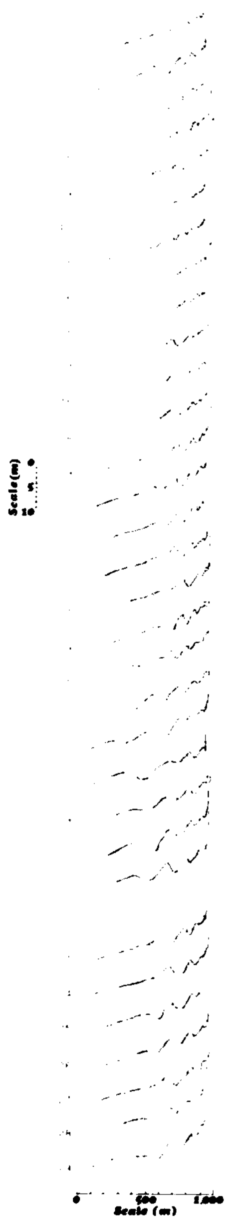

MISCELLANEOUS PAPER CERC-84-14

THE GREAT LAKES AS A TEST MODEL FOR PROFILE RESPONSE TO SEA LEVEL CHANGES

by

Edward B. Hands

Coastal Engineering Research Center

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631
Vicksburg, Mississippi 39180-0631

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The average annual water level on Lake Michigan rose 0.8 m between 1967 and 1973 causing adjustments in nearshore processes and topography. Assuming 2 mm yr as a typical rate for sea level rise, it would take 400 years to observe similar adjustments on an ocean beach. The rapid rise in average water level is one of several features that makes the Great Lakes useful for testing concepts of shore response to sea level changes.

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20. ABSTRACT (Continued).

The key assumption in the Bruun concept of response to sea level rise is that the same average beach profile is reestablished relative to the higher water elevation. This assumption was confirmed by detailed measurements over a 9-year period of 25 beach and offshore profile transects along 50 km of Lake Michigan shoreline. Complete profile adjustment lagged 3 years behind the water level change.

A simple equation was developed expanding Bruun's concept to account for (a) gains and losses of sediment from causes other than the water level variation, (b) erosion of different size sediments in the receding shoreface, not all of which would be stable in the shore zone, and (c) accretion of beach material during falling water levels.

The expanded Bruun sediment balance approach reduces the problem of estimating long-term shore response to sea level rise to the simpler problem of determining an appropriate closure depth for the responding profile. In the Great Lakes, this closure depth can be estimated as about twice the 5-year return-period wave height for the site under consideration. Use of a closure estimate based on a Froude Number, similar to Hallermeier's offshore limit, may improve transfer of the expanded Bruun approach to those areas of the ocean shore exposed to longer period storm waves.

FOREWORD

This investigation emanated from several reports developing methods to estimate the response of sandy shores on the Great Lakes to changes in water level. The basis for these reports was a series of nearshore surveys conducted over a 9-year period on the eastern shore of Lake Michigan. The first three surveys (1967, 1969, and 1971) were carried out by the US Army Lake Survey as part of its shore processes investigations. The remainder of the survey work was carried out under the Sediment Hydraulic Interaction Program at the Coastal Engineering Research Center (CERC) of the US Army Engineer Waterways Experiment Station (WES).

Assistance of the following individuals and organizations during various periods of the data collection is gratefully acknowledged: the staff of Michigan's Mears State Park who were extremely helpful during all data collection periods; the Tide and Water Level Branch, National Oceanic and Atmospheric Administration (NOAA), Rockville, Maryland, who provided lake level data; the Permit Branch, US Army Engineer District, Detroit (NCE), who helped to procure aerial photography; the Corps of Engineers Area Office in Grand Haven, Michigan, who surveyed bench marks; the 30th Engineering Battalion, Fort Belvoir, Virginia, who provided the 1976 profile survey; the National Ocean Service (NOS), NOAA, who provided the 1971 and 1975 profile surveys; and the Great Lakes Environmental Research Laboratory, NOAA, in particular Dr. J. H. Saylor (formerly with the US Lake Survey) who initiated the shore-normal profiling in 1967 and 1969 at most of the sites used in this study.

The author wishes to further acknowledge Dr. W. L. Wood and Ms. J. Pope who provided information on Great Lakes bathymetry and erosion rates outside the surveyed area. Dr. Wood, former Director of the Great Lakes Coastal Research Laboratory at Purdue University, is Chief of the Engineering Development Division, CERC; and Ms. Pope, formerly with the US Army Engineer District, Buffalo, is a Research Physical Scientist in the Coastal Structures and Evaluation Branch, CERC.

PREFACE

The text of this report was published as Chapter 8 in the 1983 edition of *CRC Handbook of Coastal Processes and Erosion* (Paul D. Komar, ed.). The Coastal Engineering Research Center (CERC) of the US Army Engineer Waterways Experiment Station (WES) is reprinting this material using funds provided by the Office, Chief of Engineers (OCE) under the auspices of the Shore Protection and Restoration Research Program. The purpose of this reprint is to provide wider access to the material contained in this investigation, especially within the Corps. This material is reprinted with permission from CRC Press, Inc., Boca Raton, Fla.

The study herein extrapolates from and synthesizes a series of reports developing methods to estimate the response of sandy shores on the Great Lakes to long-term changes in water level. The study was performed by Mr. Edward B. Hands, Coastal Structures and Evaluation (CS&E) Branch, Engineering Development Division (EDD), CERC, under direct supervision of Mr. Thomas Richardson, Chief, CS&E Branch, and under general supervision of Dr. William Wood, Chief, EDD, Mr. Charles Calhoun, Assistant Chief, CERC, and Dr. Robert Whalin, Chief, CERC.

Commander and Director of WES during publication of this report was COL Robert C. Lee, CE; Technical Director was Mr. F. R. Brown.

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THE GREAT LAKES AS A TEST MODEL FOR PROFILE RESPONSES TO SEA LEVEL CHANGES

Edward B. Hands

INTRODUCTION

The Laurentian Great Lakes system, composed of five large lakes and their interconnecting waterways (Figure 1), constitutes the largest single mass of fresh water on the surface of the earth. Regional variations and climatic factors cause long-term water level fluctuations on the Great Lakes that are uncharacteristic of ocean sites (Figure 2). The cumulative effect of persistent changes in lake levels frequently shifts monthly and annual mean surface elevations by as much as a meter in less than a decade (Table 1). Although water level changes of the type indicated in Table 1 may not appear large relative to tidal ranges at many ocean beaches, the long-term gradual nature of the changes increases their effect on shore erosion. The long duration of high water allows time for a relatively broad area of the beach and nearshore zone to adjust to the elevated water surface. This adjustment involves offshore transport of large volumes of beach material and, as a consequence, substantial shore retreat. When lake levels decline sufficiently, conditions reverse and waves transport much of the material from offshore back onto the beach. The purpose of this chapter is to summarize results of a recently completed study that has demonstrated the ability of a simple sediment budget model to accurately predict the ultimate shore response to a long-term change in water level.

Publications discussing wider aspects of Great Lakes sedimentation are far too numerous to review here, but a compilation of published and unpublished data on erosion of the U.S. shoreline was prepared by Armstrong et al.[1] An atlas by Haras[20] presented data on land use, historic flood and erosion damage, ownership, property values, and physical characteristics for all the erodible Canadian shoreline of the Great Lakes. Birkemeier[3] reported on the effects of structures on shore erosion in a southern county of Lake Michigan. Temporal changes in the rate of erosion on the eastern shore of Lake Michigan have been shown to correlate strongly with periods of storminess.[4] Seasonal and irregular variations in storminess tend to obscure the effect of long-term variations in lake level in data taken over a period of months or even a few years.

In his review of nearshore research, Hails[10] states "the biggest problem is simply the collection of data for a sufficiently long period to gain a representative picture of the changes taking place in the coastal zone". Certainly, this has been the case in attempts to document the effects of unpredictable water level changes that may fissile or reverse in a year, or either persistently rise or fall for a decade. The long-term commitment, funds, and continuity of personnel to monitor changes through-out a lake level cycle are not readily available. The long-term effects of lake level changes are obscured in compilations of time and site scrambled data that span periods of both rising and falling lake levels (Figure 3). This chapter is therefore, based on a single U.S. Army Corps of Engineers study that monitored beach and nearshore changes on a 50 km stretch of the eastern shore of Lake Michigan over a nine-year period of persistently rising and then stable annual mean lake levels.[18]

THE GREAT LAKES AS A MORE MANAGEABLE MODEL OF THE OCEANS

In many ways the Great Lakes offer a more manageable and hospitable environment than

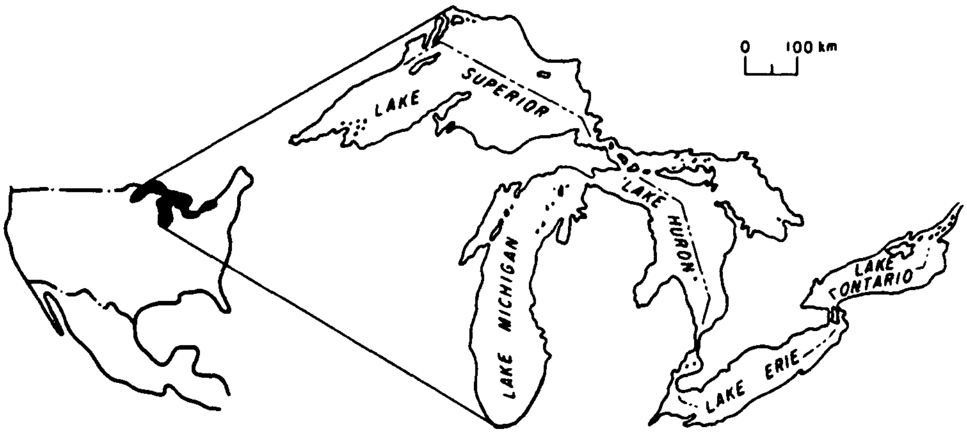

FIGURE 1. Location map for the Great Lakes.

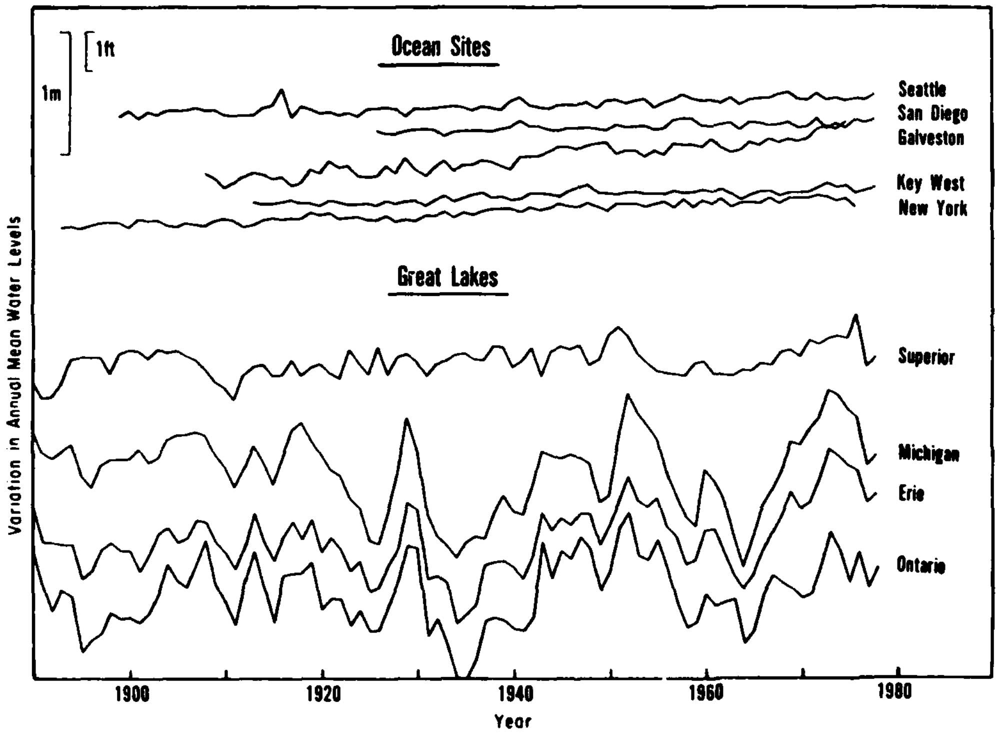

FIGURE 2. Comparison of annual mean water levels at ocean and Great Lakes sites. During rising lake levels, the shores of the Great Lakes may be submerged more in a 5 to 10 year period than most ocean sites are in a century. Reversals in trend have reduced the longer term erosive effects on the lakes, while ocean sites have been exposed to a slower, but inexorable submergence.[18]

do the oceans for the study of certain shore erosion processes. The low concentration of dissolved salt in the Lakes makes for a less corrosive environment in which to deploy instruments, while having little effect on the erosion of sandy shores. Seawater does differ from fresh water in having a lower freezing temperature and higher density. In addition, seawater increases its density as the temperature drops all the way to the freezing point,

Table 1
MAJOR INCREASES IN ANNUAL MEAN LAKE LEVEL

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

while fresh water reaches its maximum density at about 4°C above freezing. So as fresh water cools from 4° to 0°C, it expands and floats on a column of water of nearly uniform temperature near 4°C. Seawater always sinks as it cools because the temperature of maximum density is below the freezing point. Thus, there is no winter time stratification in the oceans analogous to that in the Great Lakes. In the summer, warm surface waters are usually separated from deeper cool waters by a sharp thermal and density gradient (thermocline) in both the Lakes and the ocean. The addition of a winter stratification and spring turnover on the Lakes has no known effect on shore erosion processes.

Periods of ice cover on the Lakes are primarily times of inactivity so far as shore erosion is concerned. The ice does encourage settling of fine particles nearshore, but along sand shores these deposits are usually dispersed during spring storms.

The Great Lakes system embraces a broad range of shore types: from high rocky cliffs (e.g., much of Lake Superior, the Door Peninsula of Lake Michigan, Georgian Peninsula of Lake Huron), to low gradient marshy shores (Green Bay on Lake Michigan and sections of Lake Erie), to some of the largest coastal sand dunes in the United States (eastern shore of Lake Michigan). This chapter is limited to the response of sandy shores (loose substrates) to water level changes.

The sandy shores of the Great Lakes differ principally from those on ocean coasts in a greater development of longshore bars. Sequences of longshore bars commonly extend for tens of kilometers along sandy sections of Great Lake shores (Figure 4). In this respect, the Great Lakes are more similar in nearshore bathymetry to other enclosed bodies of water, such as the Mediterranean and the Baltic Seas, than they are to most ocean beaches. Longshore bars are persistent features throughout the year in the Great Lakes while they commonly appear and disappear seasonally off ocean beaches. Because multiple bars are so well developed on the Lakes, Hands[14] was able to demonstrate a consistent increase in all bar dimensions in an offshore sequence (Figure 5). The length of bar base, bar spacing, and crest depth all increased at a fixed rate from one Lake Michigan bar to its deeper neighbor. The rate of increase in size may vary regionally depending on the overall nearshore slope, and is less where the slope is flatter. In the Lake Michigan study area where there was a 60% rate of increase in size, the overall slope through the barred field was about 0.01 (1:100).

If the better developed bars on the Great Lakes were smoothed out, the range of slopes between sandy beaches and the 10 m contour would be comparable with the range of slopes encountered off ocean beaches. In general, nearshore slopes on Pacific beaches tend to be flatter off the stormier northwest coast and steepen towards southern California. In Figure 6, a typical profile from the eastern shore of Lake Michigan can be compared with profiles from Washington, Oregon, and California. The Lake Michigan profiles have an intermediate slope similar to that found off sandy beaches in northern California. Note that longshore bars in the same depths do have similar dimensions off both lake and ocean beaches, the ratio of bar relief to depth tending to be constant for the different environments.[14,26]

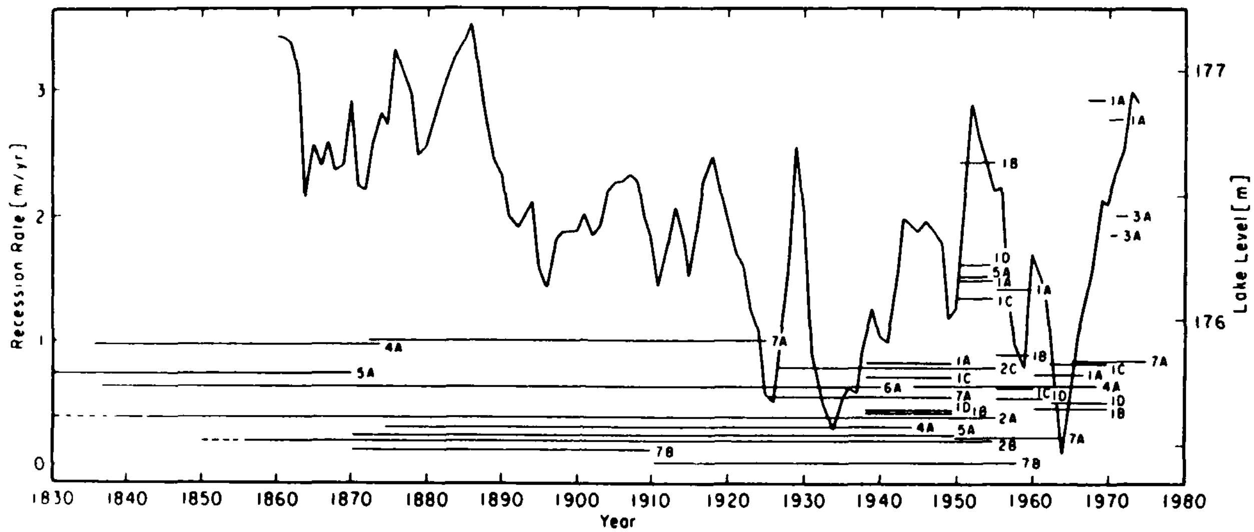

FIGURE 3. Annual mean lake level fluctuations (continuous jagged line) compared with mean bluff recession rates (straight lines). Recession rates are averages of a variable number of measurements in different sites on Lake Michigan spanning different time periods indicated by the length of each line. To examine the change in recession with time while holding the exposure and shore resistance constant, follow the rates by number/letter code. Numbers indicate sources: (1) Seibel,[54] (2) Powers,[40] (3) Davis et al.,[7] (4) Wisconsin Department of Natural Resources,[41] (6) U.S. Congress,[49] and (7) Berg and Collinson.[2] Letters indicate locations. From Hands.[14]

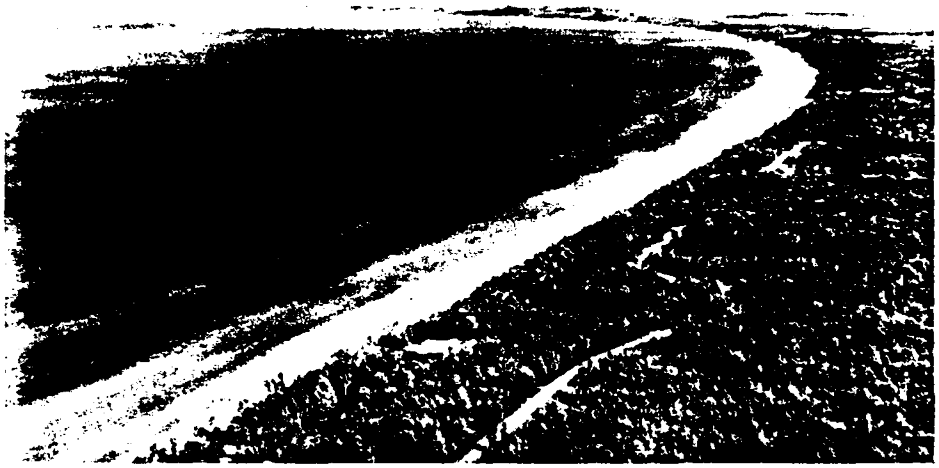

FIGURE 4. Longshore continuity of bars on the eastern shore of Lake Michigan. The inner two to three bars are usually visible when viewed from high bluffs and dunes along the shore.[18]

Storms erode the lake beaches and create another type of submerged sand ridge between the beach and the first persistent longshore bar. This storm ridge and its associated landward trough are sometimes referred to as the "ridge and runnel". In contrast to persistent longshore bars, the ridge is a smaller, temporary feature that may be linear, or doubly shoretied. After storms, these ridges characteristically migrate landward and weld to the beach. Davis et al.[6] compared ocean and Great Lake ridge and runnels, concluding that the overall morphology and internal structure are quite similar. Great Lakes ridges are, however, smaller in scale and migrate much more rapidly. Davis et al.[6] attribute these differences to the lack of tides on the Lakes.

The presence of a sequence of longshore bars also effects the sorting of Great Lakes nearshore sediments (Figure 7). Well-sorted sands become progressively finer as one moves from one bar crest to the next offshore. The intervening troughs, however, are lined with much coarser material. The coarsest and most poorly sorted sands are usually in the outer or next to outer trough.

Both lake and ocean waters respond to an onshore wind stress by piling up water on the beach and creating a temporarily inclined water surface. However, when the wind stress dies down on the Lakes, the water surface begins to oscillate as a function of the length and depth of the basin. These oscillations or seiches may affect onshore-offshore movement of sediment, but measurements of this phenomenon have not been obtained. The Lake Michigan study sites, upon which analogies in this chapter will be drawn, are not subject to extreme set-up or seiches typical of other sections of the Great Lakes. Therefore, these phenomenon introduce no difference between ocean and lake erosion processes that need to be considered here.

The major difference in erosion on the lakes and oceans results from the contrasting wave climates caused by restrictions in fetch on the Lakes (Chapter 1). A restriction in fetch results in a ceiling on both the wave height and wave period. The restricted size of the Great Lakes also limits the transfer of energy from short period seas to longer period swells. This shift of energy to longer period swell is characteristic of oceans where the waves travel

ADDITIONAL SUPPORT FROM HISTORIC DATA

In an earlier study, Hands[16] had reported an apparent north to south increase in the rate of historic shore retreat on Lake Michigan. The trend was suggested by plotting historic shore recession measurements[30] versus the position of the shore measurements projected on a mid-lake axis (Figure 14). Examination of longshore variations in resistance of the shore to erosion, in offshore bathymetry, wave power, and winter ice protection, all failed to provide any explanation for this apparent increase in erosion toward the south.[16] The basin is slowly tilting, however, as it continues to recover from Pleistocene glacial depression centered near Hudson Bay to the north. This is confirmed by geomorphic,[27] geophysical,[40] and geodetic[28] evidence of differential uplift, as well as by differences in the water level records up and down the shore.[23] Both the recession data and the water level data cover approximately the last 125 years. The least square regression of the 94 bluff measurements was 19 m per century per 100 km along the axis of tilt. The rate of tilt obtained by comparing 1929 and 1955 releveling data (0.087 m/100 km yr) was roughly comparable to that estimated from lake level differences (0.063 m/100 km yr). Thus, each cm of submergence would have to be responsible for between 1 to 4 m of shore recession if the regional trends in recession were to be attributed solely to submergence. For each unit that a high bluff recedes, more sediment is supplied to build the outer profile than would result from equal recession on a low shore. Interestingly, the increase in historic recession per unit of subsidence is greater on the relatively low western shore of Lake Michigan, in keeping with the concept of sediment balance.

LIMITS OF PREDICTION

Assuming constancy of profile shape, we have seen that the problem of predicting the ultimate shore erosion in response to a long term water level change becomes equivalent to simply identifying a profile closure depth. The confirmation of this concept with Lake Michigan data, encouraged a generalization to other regions of the Great Lakes where wave energies, and therefore closure depths, were different. Tables of closure depths for all sections of the U.S. shoreline of the Great Lakes were prepared based on the assumption that closure depth is proportional to the height of waves forecast with a 5-year return period.[19] The proportionality constant evaluated on Lake Michigan was about 2; i.e., the closure depth was equal to about twice the height of the 5-year return period wave height on the existing shore test site.

Theoretically, the depth of bottom motion should depend on the wave steepness, the shoaled and refracted wave height, and the grain size. The roles of these variables are however usually secondary to variations in offshore wave height. Given the restricted range of wave periods and sediment sizes off sandy shores of the Great Lakes, it was felt that a simple correlation of closure depth to wave height was justified. Over a period of varying wave conditions, it is reasonable that closure depth depends more strongly on the character of the higher waves. The 5-year return period wave was chosen because it was readily available and any consistent relative measure is probably satisfactory for extrapolation within the Great Lakes.

The greater response to submergence ratio, x/z, in the historic Lake Michigan study (1:100 and 1:400), as compared to the ratio (of 1:69) obtained during the shorter, more precise study, suggests that the dimensions of the responding profile expand and/or sand leakage occurs over a more extensive area as time scales increase. Thus, the results of monitoring profile responses on Lake Michigan did not indicate the ratio of wave height to profile relief (H_s/Z) that would be appropriate for periods of time greatly longer than 10 years. In as much as extreme storms during a 100 or 1000 year period would move sediment deeper,

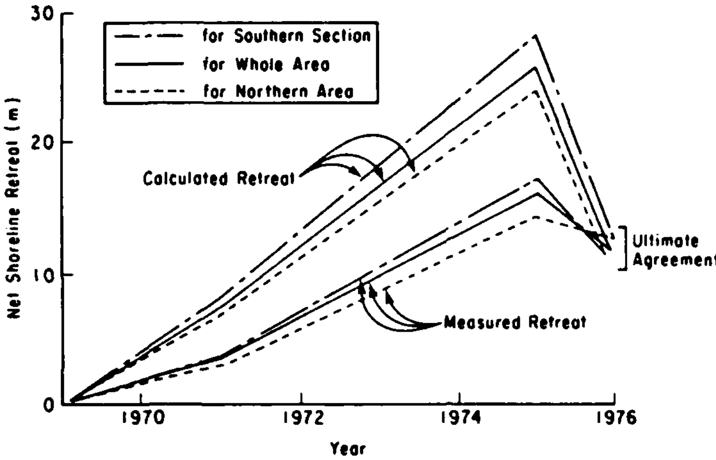

FIGURE 13. Calculated versus measured shoreline retreat. The predicted ultimate retreat, in response to post-1969 changes in mean lake level, exceeded the observed retreat by more than 100 percent in 1971 and by about 50 percent in 1975 presumably because the active profile had not had time to completely readjust to the higher water levels. Almost perfect agreement had developed by the time of the last survey, 3 years after the lake level maximum.[18]

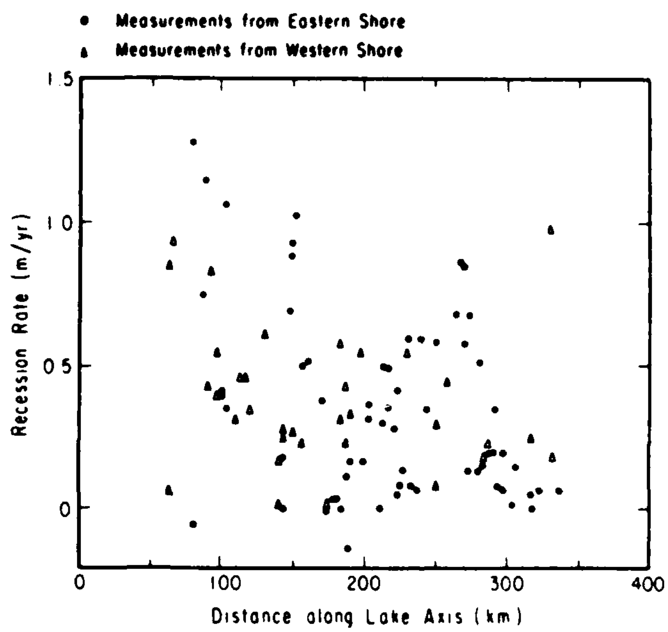

FIGURE 14. Historic rate of recession vs. measurement position projected on Lake Michigan mid-lake axis. Rates of recession are based on data from Powers (1958) and cover a period of about 125 years. There is a trend toward lower recession rates at the more rapidly rising, northern end of the basins.[5]

Table 2
PREDICTED AND OBSERVED PROFILE RETREAT

	Survey Periods		
Study Areas	**1969-1971** **z = 0.12 m** **X = 870 m**	**1969-1975** **z = 0.39 m** **X = 1020 m**	**1969-1976** **z = 0.20 m** **X = 923 m**
	AVERAGE HEIGHT, Z (m)		
Northern section (stations 1 to 15)	10.84	12.15	12.50
Southern section (stations 16 to 29)	12.90	14.28	14.80
Whole area (stations 1 to 29)	11.86	13.21	13.60
	PREDICTED RETREAT, Xz/Z (m)		
Northern section	9.63	32.74	14.77
Southern section	8.09	27.86	12.47
Whole area	8.80	30.11	13.57
	OBSERVED RETREAT x (m)		
Northern section	4.6	20.0	12.6
Southern section	3.6	16.8	14.8
Whole area	4.3	18.8	13.6
	OVERPREDICTION (pct)		
Northern section	109	40	10
Southern section	164	66	−7
Whole area	117	45	0

to 1975), thus partitioning the original data into nine individual, though not independent tests (Table 2). Considering prediction versus measurements, the predicted retreat from 1969 to 1971 was too high for all three areas (117% high for the areas as a whole). The prediction for 1969 to 1975 was also high, but not as far off as before (45% high for the whole area). These overestimations of retreat are attributed to the fact that profile retreat was actually lagging behind the lake level rise. Rising water levels establish a potential for erosion and realization of that potential requires sediment redistribution, i.e., work which depends on the energy being available. Eventual convergence of measured and predicted retreat in both regions, 3 years after annual lake levels had stabilized, suggest that several storm seasons may be required to readjust the profile to changes in mean water level of several tenths of a meter (Figure 13).

Between 1967 and 1975, persistent rapid shore recession occurred at almost all sites, as documented by five separate field surveys.[17] The last of these surveys indicated no decrease in recession rates even though the annual mean lake level had peaked 2 years earlier. Then recession rates dropped dramatically in 1976. The beach even prograded for the first time at 12 of 34 survey sites. This sudden interruption of the previous erosive trend indicated equilibrium was finally being approached. The continuation of high recession rates after lake levels peaked was consistent with the assumptions of the sediment balance model, as were the early overestimates of recession. The crucial proof of the model's usefulness, however, was that it correctly predicted shore retreat in 1976 just as the long-term period of high erosion was coming to a close.

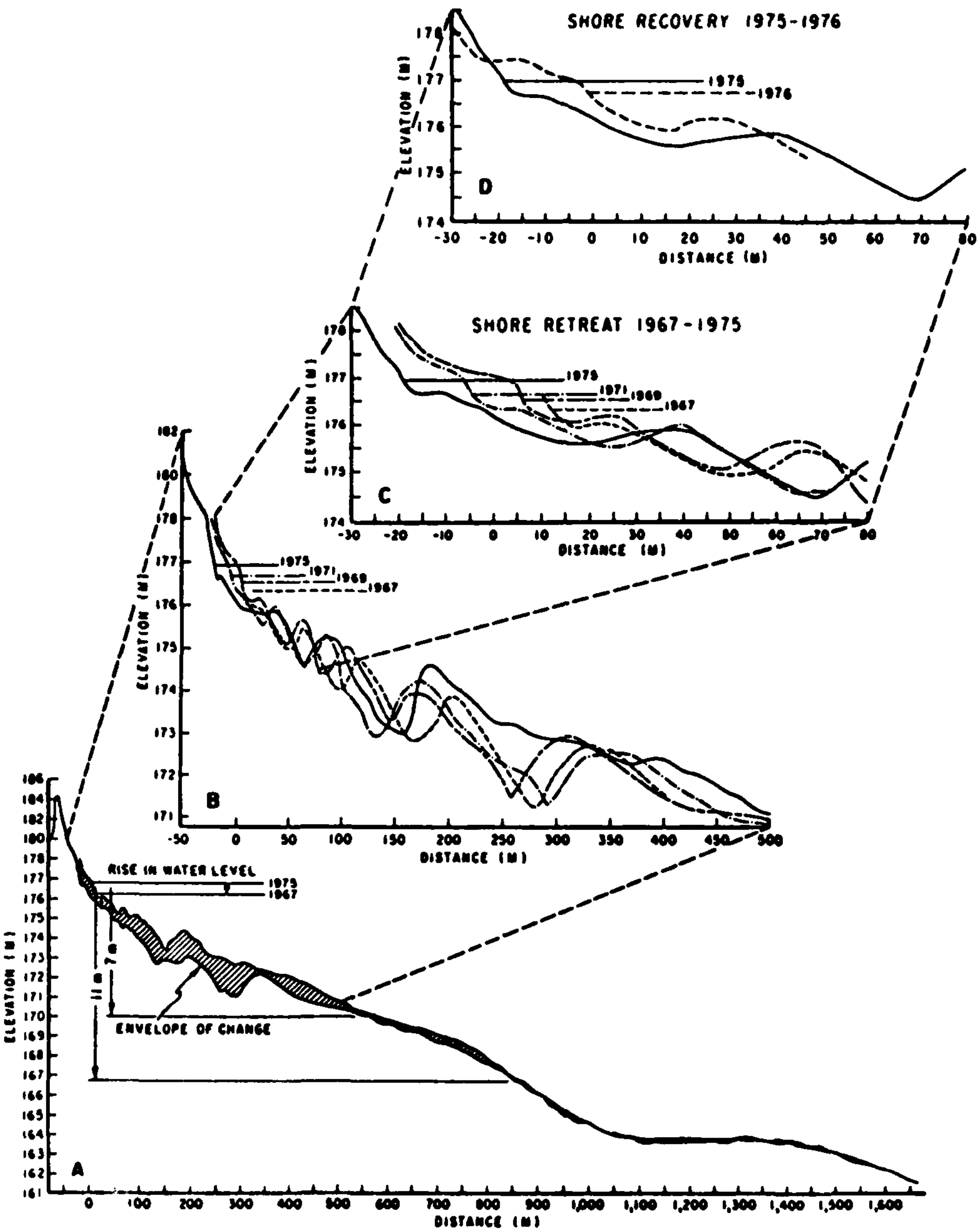

FIGURE 12 Measured profile adjustments over a 9-year period of rising and then stable water levels on Lake Michigan. Bars move upward to maintain constant depth beneath the rising water surface.

the results clearly confirm the appropriateness of the equilibrium-sediment balance approach when applied in the proper setting.

Closure depths were deeper south of Little Sable Point than to the north. The eroding dunes were also higher there, which even further enlarged the vertical dimension of profile adjustment. Consequently the equilibrium prediction can be applied separately to the two regions. Likewise, because additional surveys were conducted in 1971 and 1975, separate predictions could be applied as well to these shorter time intervals (1969 to 1971 and 1969

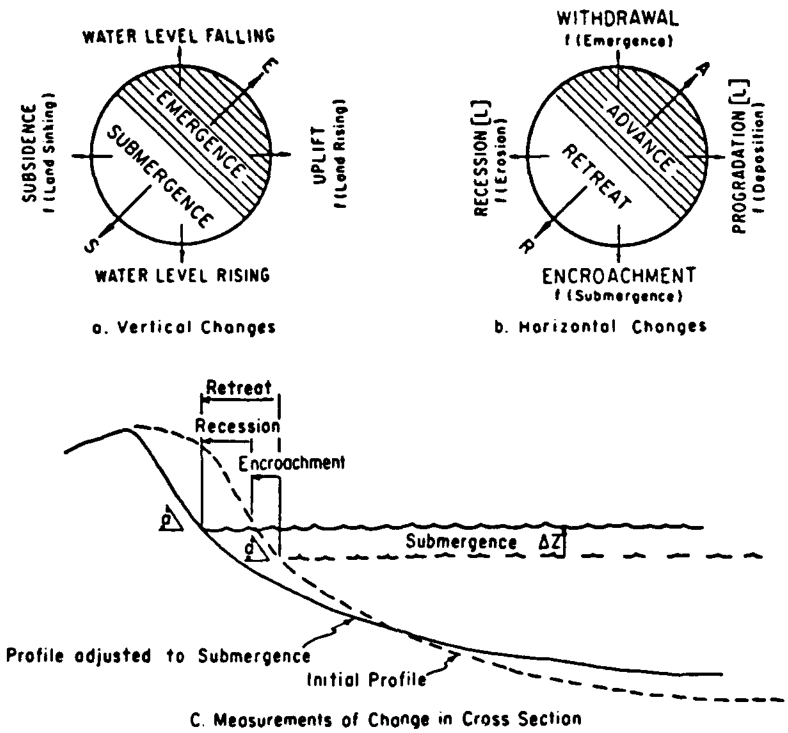

FIGURE 11. Terminology of shore retreat where retreat = encroachment + recession and encroachment = z cot α.[17]

stretch was monitored (7 years), the sizable increase in lake level experienced during the study, and the near-ideal site conditions (absence of silt and clay in eroding shore deposits, no overwash, hurricanes, seiches, submarine canyons, fluvial or longshore sediment input to contend with) makes this study the most realistic field test to date of an equilibrium profile response to water-level changes.

As points of a bar bifurcation migrated, the number of bars on some profiles varied, but overall the number and size of bars remained constant throughout the study. In keeping with the equilibrium assumption, the bars migrated landward and maintained a nearly constant depth beneath the gradually rising lake level (Figure 12). The landward migration of bars and troughs created shore parallel bands of alternating erosion and deposition rather than the simple lever point of Figure 9. Landward of the inner trough, erosion removed 10.3 m^3 per meter of beach per year averaged over the study period. Deposition measured offshore compensated for the inshore volume losses verifying conservation of sediment volume as required by the model. But how well would the sediment balance model have predicted the observed shore retreat?

Measurements of the width of each profile from the vegetated dune line to the closure depth for each station averaged X = 923 m. The heights of the scarps which waves had cut in the foredune, when averaged and added to the average closure depth, established the vertical dimension of the adjusting profile (Z = 13.6 m in Equation 1 and Figure 9). Equation 1 is applicable because Q = 0 and R_A = 1; thus the ratio X/Z times the measured water level change (z = 0.20 meters) yields a predicted ultimate shore retreat of 13.6 meters. The retreat actually measured between 1969 and 1976 also averaged − 13.6 meters. Considering the measurement and sampling errors involved in determining each independent variable, a predictive capability of less than a tenth of a meter certainly is not claimed, but which "adequately" represents the "average" profile shape before perturbation by a shift in water level. By assumption, shore erosion eventually returns the profile to this same shape after it is displaced as a result of the water level change (Figure 9).

A willingness to accept equilibrium as a reasonable approximation is not inconsistent with recognition of seasonal, storm, or other temporary profile fluctuations. Careful judgment should be made on a case-by-case basis, if field profiles claim to represent quasiequilibrium conditions. Generally, the claim will be more reasonable the longer the time frame and the wider the spatial extent of the study. Greater sampling density in time and space produce more precise estimates of mean parameters.

DIFFICULTIES AVOIDED IN THE GREAT LAKES

The above discussion has shown that the Bruun concept is theoretically sound but is difficult to apply in the field. However, some of these difficulties can be avoided in the case of the Great Lakes.

Establishing a realistic closure depth (Item 3) depends on accurate repetitive profiling, the profile errors increasing with distance from shore. Fortunately, the bottom drops off to suitable depths relatively rapidly in the Great Lakes study area. Furthermore, the Lakes are free from tidal variations as well as from long-period swell that complicate profile comparison. Although the Great Lakes are notorious for their large storm surges and seiches, extensive water-level measurements verify that they are negligible in the present data set and so did not affect the determination of the closure depth.[18]

The difficulty of determining sediment losses (Item 2) on the Great Lakes is greatly simplified by the absence of submarine canyons, hurricanes, and overwash events. All rivers entering eastern Lake Michigan flow through deep inland sediment traps. Inlet losses have a negligible effect on the overall sediment budget for the broad study area. Thus, in the present application Q (in Equation 4) can be taken as essentially zero.

The section of shore is an isolated littoral cell, so the only process supplying new sediment to the active profile is shore recession. Furthermore, shore deposits and backshore bluffs within the study area contain less than 1 percent silt, making it unnecessary to correct for any unstable fine fraction (i.e., $R_A = 1$ in Equation 4). Thus, a number of site-specific attributes simplify the sediment balance for this particular study area.

SHORE RETREAT MEASUREMENTS

Encroachment refers to the immediate loss of beach width due to *submergence*. The total shore retreat will exceed encroachment as the shore *recedes* due to erosion (Figure 11). Between 1969 and 1975 (a period of persistent high water levels on Lake Michigan) the overall shore retreat exceeded encroachment by a factor of 5 (average retreat = 17.9 m, but only 3.4 m was due to encroachment). The final amount of encroachment at individual stations, while predictable, gave no clue as to the final amount of shore retreat.[17] Shore recession depends on the local sediment supply plus the exposure and resistance of the beach to erosive forces. Within the range of conditions observed on the lake, flatter foreshores showed no tendency to recede more or less than steeper foreshores. Moreover, shore recession continued for some time even after the water levels began to decline. Hence, encroachment, depending only on steepness of the foreshore and the change of water levels, though easy to predict, is a poor measure of total shore retreat.

FIELD CONFIRMATION OF THEORY

The extent of shore covered (25 profiles spread over 50 km), the length of time the entire allowing the closure point to move in infinitesimal steps with the water surface. This approach results in the more precise relationship:

$$x = X \ln \frac{Z}{Z - z} \qquad (4)$$

Equation 4 is generally unnecessary because the change in water level, z, is usually so small relative to the total height, Z, that equations 1 and 4 provide essentially the same results. For example, if $z < 0.1Z$ all results agree within less than 10%.

Thus, the simple expression $x \sim zX/Z$, is not only valuable as a close approximation, but is also most useful because it is easily (a) recalled by visualizing the adjustment of two rigid translations, (b) explained in the same manner, and (c) used as a quick mental check on the ultimate retreat expected for various values of the independent variables.

A Realistic Closure Depth (Item 3) — Determining a realistic closure depth is usually extremely difficult. The most direct approach is to compare historic bathymetric surveys of the site in question. Unfortunately, adequate survey data of this type are rare. Neither pier nor stadia surveys extend deep enough, and if a hydrographic survey does extend to deep water, allowances must be made for the fact that both sounding errors and boat-positioning errors usually increase significantly with depth and with distance from shore. The effect of long period swell may be impossible to distinguish from real bathymetric changes, and apparent bottom waves may or may not have been smoothed out during data reduction. Some surveyors may even "adjust" their profiles to obtain the best fit offshore, assuming there has been no change there. It is thus often impossible to substantiate apparent offshore changes unless you have taken repetitive profiles yourself.

Finally, even if you have such profiles, evaluation of the closure depth requires two surveys separated by an appropriate time period during which profile adjustment actually occurred in response to a known change in water levels. Hallermeier[11] demonstrates the dependence of profile closure depth on local wave conditions for essentially stable water levels. The difference between depths of closure at two sites with identical wave and sediment characteristics, one with a stable mean water level and the other with a recently displaced water level, has not been studied. It seems plausible that storm waves could cause a net profile change where equilibrium had been perturbed by the recent shift in the mean water level, and yet cause only sediment motion and (almost by definition) no net change in bottom elevation where the profile was in equilibrium with a constant water level. This being the case, real water level changes are essential if repetitive profiles are to reveal a closure depth suitable for testing the Bruun concept. Clearly, many problems plague the determination of the appropriate closure depth and therefore discourage application of Bruun's concept for predicting future shore retreat.

Sediment Losses (Item 2) — By adding terms, the Bruun concept can be extended to complicated, nonequilibrium situations.[18] This is useful, however, only if field data permit accurate evaluation of the added terms. Often field data are inadequate. The average rate of uncompensated sediment flux, Q, across the control boundaries must be known. Submarine canyons, hurricanes, and the long term effect of winds complicate this evaluation. Lastly, the composite textural characteristics of the active beach may be necessary to evaluate R_A.

Adequacy of an Equilibrium Model (Item 1) — Use of equilibrium assumptions to model dynamic coastal changes also deserves scrutiny. The idea of an "equilibrium beach profile" has had a long history (e.g., Reference 9, Fenneman, 1902); however, opinions still differ as to exactly what the concept actually entails. By one definition, the profile of equilibrium refers to the ultimate shape which coastal processes strive to impart to a beach. Of course nature seldom remains constant long enough for a strict equilibrium to develop. In the present context, the term *equilibrium profile* refers to a curve of fixed size and shape

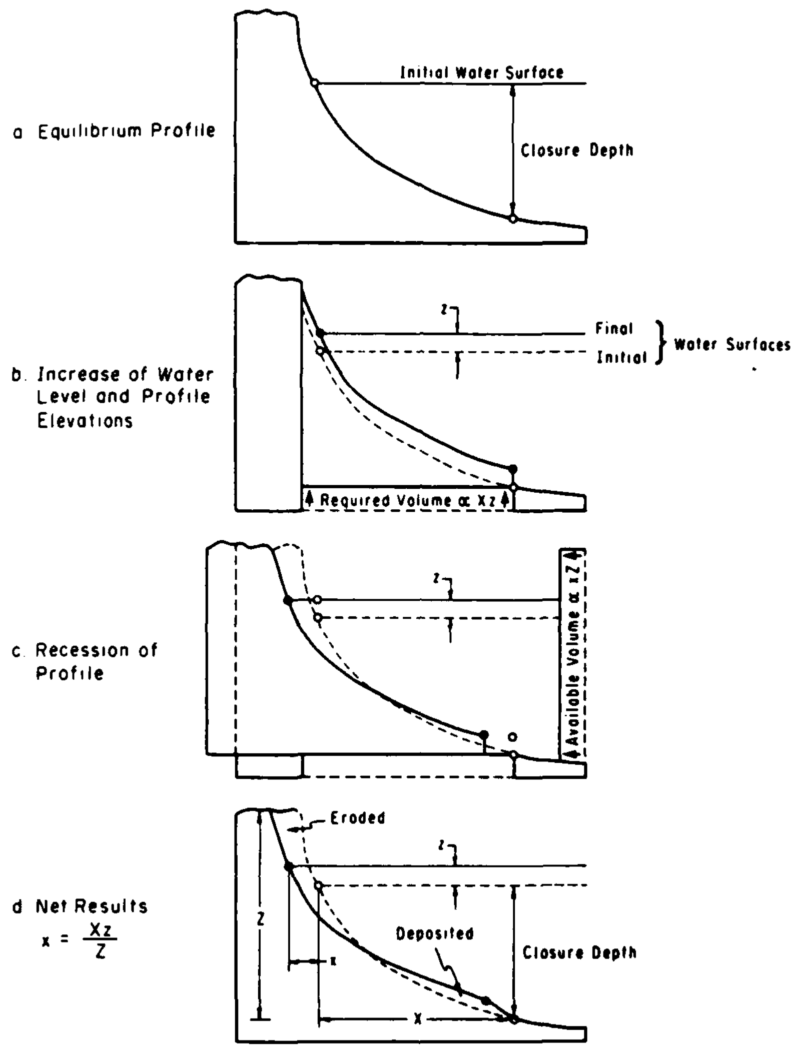

FIGURE 10. A schematized view of profile adjustment as two rigid translations, demonstrating the basis for the Bruun Rule (Equation 1).[18]

the closure depth below which the bottom presumably does not adjust to surface wave and current conditions. To estimate the ultimate shore retreat, the adjustment of the active profile is next depicted as two rigid profile translations. The first translation moves the active profile (i.e., the profile between the closure depth and the upper point of profile adjustment) up an amount z and reestablishes equilibrium depths below the elevated water surface (Figure 10b). This step requires a volume of sediment proportional to the product of X (the width of the active zone) times z (change in water level); the volume is made available by the second translation which is a recession of the profile. Figure 10c shows that x units of recession provide a volume of sediment proportional to the product of x times z (the vertical extent of the active profile from the closure depth up to the average elevation of the highest erosion on the backshore). Equating the volumes produced and required per unit length of shoreline by these two translations yields Equation 1.

In reality, both translations occur simultaneously and the closure point migrates upslope as the water level rises. A more formal development would integrate between profiles, sediment volume in time t across the boundaries of a control area with longshore length, Y, then the earlier estimate of retreat should be reduced by Qt/YZ. In its general form, the predicted shore response becomes:

$$x = \frac{zX\,(R_A)^{-g(z)}}{Z} - \frac{Qt}{YZ} \qquad (3)$$

as given by Hands.[18] Thus without introducing anything really new, Bruun's[5] concept can be applied to more complicated nonequilibrium conditions, and to the predictions of shore response as a consequence of falling as well as rising water levels.

DIFFICULTIES IN APPLYING THE SEDIMENT BALANCE APPROACH

There has been a continued interest in Bruun's concept since it was initially expounded in 1962. A special symposium on this subject was held in 1979.[33] Yet, in spite of widespread evidence of a sea level rise, the sediment balance approach has not been widely applied for predictive purposes. The following difficulties may explain a reluctance to routinely apply this approach:

1. Skepticism as to the *adequacy of an equilibrium model* for explaining short-term dynamic changes
2. Difficulties in determining *sediment lost* from the active zone
3. Problems of establishing a *realistic closure depth* below which water level changes have no effect on profile stability
4. Confusion arising from a typographic *error in one of the equations* defining profile retreat[5]
5. The perplexity caused by a *discontinuity in the profile* at the closure depth which appeared in the original and all subsequent diagrammatic sketches illustrating the concept

The first three difficulties (1, 2, and 3) warrant serious consideration before applying Equation 3; items 4 and 5, although perhaps confusing, should in no way discourage or limit use of Equation 3. The following paragraphs address each of these difficulties in reverse order.

Discontinuity in the Profile (Item 5) — Previous diagrams have illustrated the adjustment of a profile to higher water level by literally disconnecting the responding part of the bottom from a static region offshore. The apparent profile discontinuity at the juncture between the static and responding regions has some didactic value as it emphasizes congruency between initial and final profile shapes in the active region. Unfortunately, it also creates the impression that the model is inadequate for explaining the transition between the active and static parts of the profile. This discontinuity is not, however, an inherent part of the concept. It is only an artifice of the diagrams. Rigidly translating a profile upward and shoreward does not necessarily lead to a discontinuity nor even a change in slope as is demonstrated later in this report.

Error in Equation (Item 4) — Bruun's equation (Reference 5, Equation 1a, p. 124) is dimensionally incorrect as published. This apparent typographic error may have confused and discouraged some readers from giving Bruun's concept their full consideration. The problem equation is, however, unnecessary to the development of his concept which was correctly expressed in Equation 1b of that paper. The validity of the Bruun concept and of Equation 1 in this chapter is demonstrated geometrically in Figure 10.

Figure 10a depicts a nearshore profile in quasiequilibrium with wave-related forces. Note

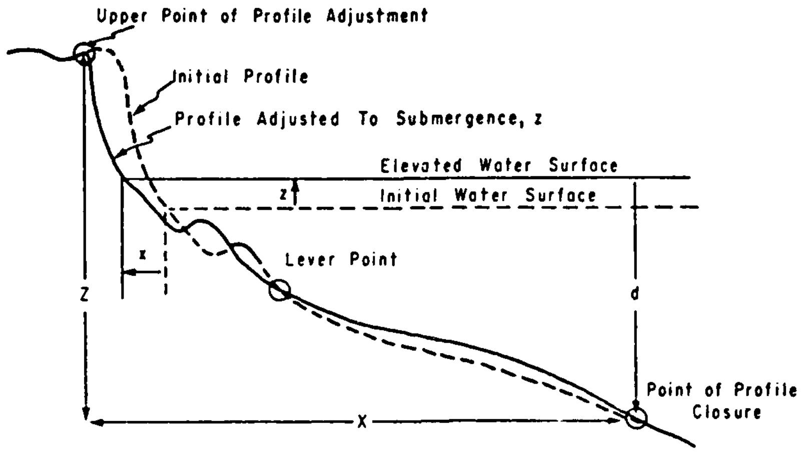

FIGURE 9. Sketch of profile measurements required to predict shore adjustment to an elevated water surface. Providing there is no net gain or loss outside the control volume, constancy of profile shape requires that the ultimate shore retreat x be approximately zX/Z.

$$x = \frac{zX}{Z} \qquad (1)$$

If only P percent of the shore-eroded sediment remains in the active zone, greater shore recession will compensate for this loss. One method of estimating the proportion of shore-eroded material lost is to use the textural characteristics of the active beach as a guide. This method was originally proposed by Krumbein and James[25] to estimate the volume of material required to build a beach that will be of design dimensions after winnowing by wave action. Calculation of the overfill ratio, R_A, for beach fill has since been refined by Dean[8] and by James.[22] Hobson[21] explains procedures for estimating R_A. The same procedures will apply in the case of profile response due to high water, except that the "borrow material" characteristics must be based on a composite sample of the eroding section of the shore, i.e., the upper beach in the case of increases in lake level. If the water level declines, the lower part of the responding profile is eroded to supply material to prograde the upper profile. In this case the "native material" characteristics must be based on a composite sample of the lower profile (i.e., the zone of offshore erosion). In either case, the native material characteristics must be based on a composite sample of the entire responding profile, from the upper point of profile adjustment to the offshore point of profile closure (Figure 9). If there are no longshore imbalances, the increased shoreline retreat will be

$$x = \frac{zX\,(R_A)^{sg(z)}}{Z} \qquad \begin{array}{l} \text{where } sg(z) = 1 \text{ if } z > 0 \\ \text{where } sg(z) = -1 \text{ if } z < 0 \end{array} \qquad (2)$$

When eroding shore deposits are too fine the overfill ratio is positive, $R_A > 1$, and the predicted retreat is increased by a factor of R_A. When lake levels fall and eroding offshore sediments are too fine, R_A is again positive, but the predicted response (shore advance) must be decreased by a factor $1/R_A$. The exponent sg(z) serves to flip the overfill ratio from the numerator to denominator as appropriate.

Any longshore imbalances, or other uncompensated exchanges of sediment beyond the control volume, must also be accounted for to correctly predict the total shoreline change. Losses can occur offshore, onshore, or alongshore (Chapter 1). If Qt is the net exchange of

Most stretches of the Great Lakes shore are exposed to fetches greater than 100 km and some stretches of the southeastern shores of the lakes are exposed to 300 km fetches (Figure 1). As can be seen in Figure 8, as long as there is at least 100 km of fetch, the depth of bottom disturbance is not limited for a developed sea under persistent winds of up to 12.5 knots (6.4 m/sec). This means for example, a persistent wind with an average speed of 12 knots has the same potential for moving sediments to a depth of 13 m or 42 ft, regardless of whether it blows over the lake or an infinite ocean. At wind speeds above 12 knots, the available fetch may or may not limit the depth of sand motion. For example, assuming a fetch of 100 km, a persistent 31 knot wind would have the potential for moving sediment down to a respectable depth of 30 meters on the Great Lakes. Theoretically, this wind could cause sand motion much deeper than 100 m if the fetch were unrestricted; but as seen in Figure 8, this would require a wave generation area approximately 600 km wide in the direction of the average 31 knot winds. Thus, fetch may be limited not just by basin dimension, but also by the size of the storm.

Even though restricted basin dimensions do introduce a major difference in wave climates and, therefore, in the profile shape, Figure 8 nevertheless suggests that profile development in the Great Lakes and ocean is similar down to depths far below those expected for a small lake. And for winds of modest speeds, the size of the basin does not limit the depth of sand motion.

The three auxillary vertical axes in Figure 8 refer only to waves that were not fetch limited. These axes demonstrate the general feature that shoaled wave heights may be either greater or less than the deep water wave heights, depending on the point where they are measured (Chapter 1). The equations relating wind speeds to resultant wave length and height, as well as those described in the transformations of length, height and bottom orbital velocities as the wave shoals, are all well known, but the nearly constant proportionality between depth of disturbance and wind speed for a fixed fetch (evident in Figure 8) has not, to this author's knowledge, been previously noted. The nested double iterations necessary to obtain depth of disturbance from wind speed and fetch, obscures the nearly linear dependence between wind speed and depth of bed disturbance by fetch-limited waves.

In review of the Great Lakes as a model for oceanic shore erosion, the principal differences are: lack of tides, lower wave heights, and the lack of long-period swell on the Lakes. All three of these major differences do have the advantage, however, of facilitating field work. While maximum wave heights are less on the Lakes, they are nevertheless sufficient to move sediment out to considerable depths. With the exception of certain features of bar development, nearshore zones on the Lakes are generally similar in profile to ocean beaches. The lack of tides and the restricted range of wave heights and periods may explain the full development of a sequence of persistent longshore bars on enclosed seas.

IDEALIZED SEDIMENT BALANCE

This section presents an idealized concept for predicting profile adjustment to new water levels simply as a function of the magnitude of the water level change and two measurements of nearshore profile geometry. Corrections are then added to account for offshore losses of fine sediment and longshore imbalances in sediment flux.

As described by Bruun,[5] an increase in the mean elevation of the water level tends to shift the equilibrium sand profile landward. As water levels rise, erosion prevails on the upper beach causing the shoreline to recede. Conceptually, this shore erosion supplies material to build upward the outer part of the responding profile. If it is assumed that the initial profile shape will be reestablished farther inland at a distance above its initial position equal to the change in water level z, the ultimate retreat of the profile x can be calculated from the dimensions of the responding profile, X and Z, as depicted in Figure 9. This yields the simple relationship

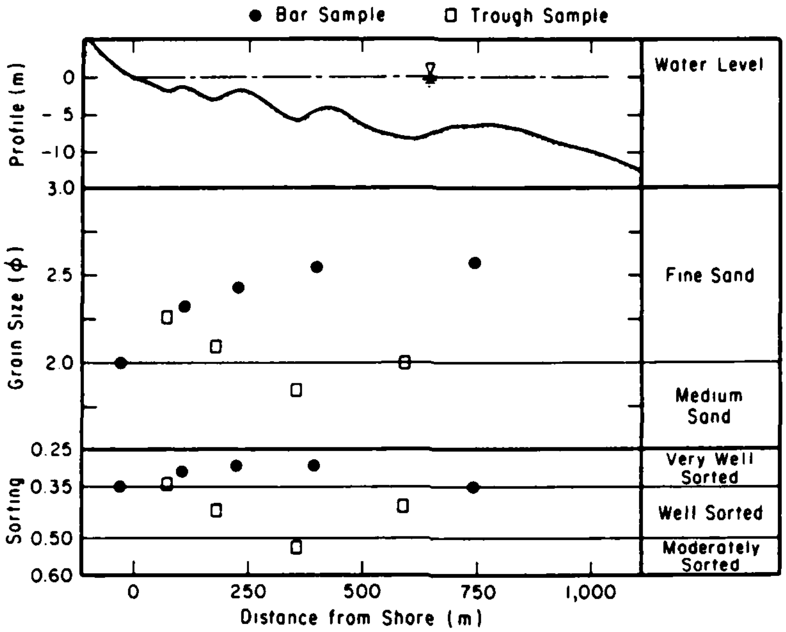

FIGURE 7. Nearshore profile and sediment distribution from a Lake Michigan beach. Well-sorted sands become progressively finer on the deeper longshore bars. Poorly sorted sand and gravel are coarser in deeper offshore troughs.[12]

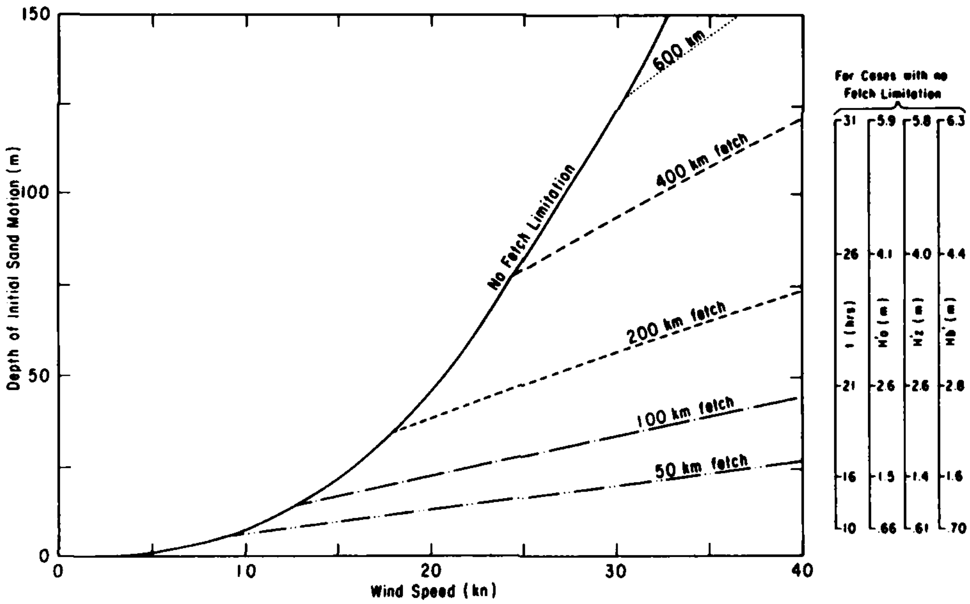

FIGURE 8. The effect of a restricted fetch in limiting the maximum depth of bed motion. Deep water wave conditions were forecast for various fetch distances and average persistent wind speeds (X axis). As waves move into shallower water, orbital velocities increase at the bed. The depth at which the bottom velocity reaches 15.24 cm/sec (0.5 ft/sec) is taken to be the depth of initial sand motion (Y axis). Four auxillary axes on the right indicate the duration of the winds necessary to develop the conditions depicted in the figure and also provide a feel for the resulting significant wave heights in deep water (H_o'), over the point of initial sand motion H_i') and at breaking (H_b'). The auxillary axes are nonlinear and assume no fetch limitations.

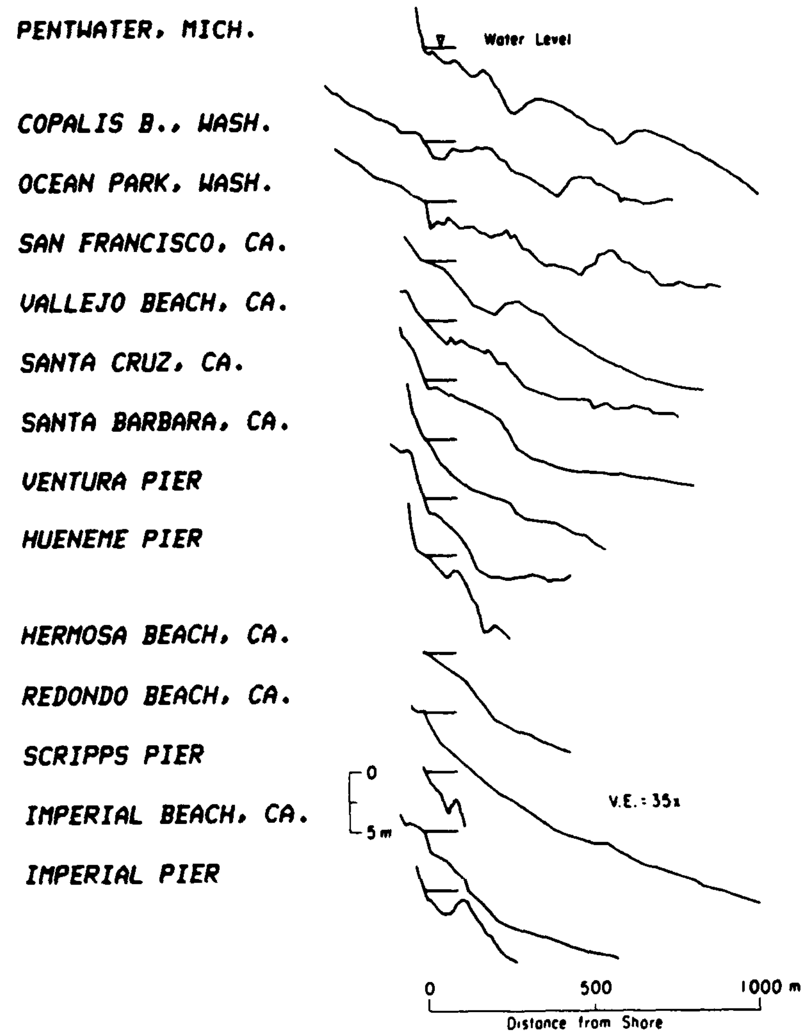

FIGURE 6. The smooth, well-developed bar pattern of the top profile is typical of the Lake Michigan study area. Pacific coast profiles (arranged from north at the top to south at the bottom) sometimes have one or two bars of a size similar to those at the same depths on the Lakes, but ocean coast profiles generally lack the orderly progression of a multiple-bar field which is typical of enclosed seas. The overall slope of the Pacific nearshore profiles increases from north to south. Smoothing out the bars, the Lake Michigan profiles have an intermediate slope similar to that of sandy sections of northern California

equal to one half the wave length the bottom velocity should be about 4% of that at the surface. For most purposes it is assumed that the wave is not affected by the bottom before reaching this depth. Detailed analyses of wave conditions leading to motion of bottom sediments have been given by Komar and Miller[24] and Hallermeier.[12] For simplicity here, the depth at which the waves affect the bottom is taken to be the depth at which orbital velocities reach 15 cm/sec. This depth of initial bed motion will depend on both the height and period of the waves and assumes a rough cohesionless sand bottom. The depth of initial bed motion presented in Figure 8 was obtained by predicting fully-developed and fetch-limited deep-water wave characteristics using an empirical forecasting procedure based on the JONSWAP spectrum. The other formulas that were used in the construction of Figure 8 are also well established.

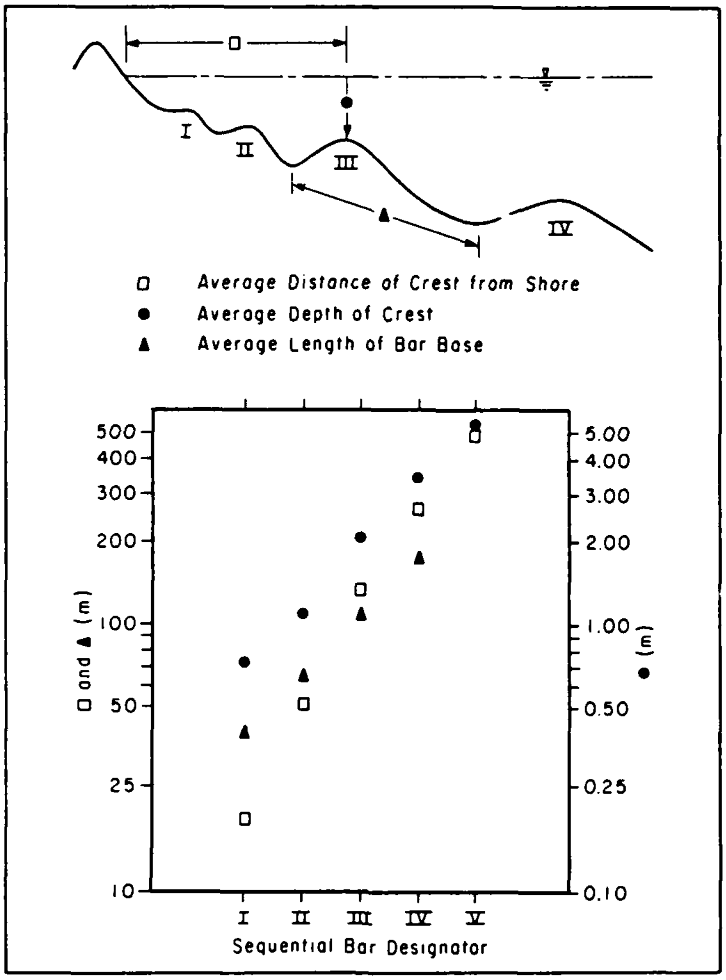

FIGURE 5. Average bar dimensions vs. position in an offshore sequence. Bar dimensions increase offshore across multiple bar fields, forming regular geometric progressions. Both the depth of the bar crest and the length of bar base appear to increase at the same rate. The rate may vary from site to site, and will be less where nearshore slopes are flatter. The above data are from a site on Lake Michigan where the slope is 1 in 100. Successive bars are about 60% deeper and 60% longer in cross-section than their landward neighbor.[14]

perhaps thousands of miles between the storm generation area and the beach. The distinction between sea and swell may be ignored on the Great Lakes.[31] In fact, wave periods rarely exceed 10 sec whereas periods in excess of 20 sec can occur on the oceans.[35] Even though restricted fetch does limit maximum wave development, the sinking of seasoned ocean vessels during their first winter voyages on the Lakes gives testimony to the frequent underestimation of Great Lakes storms by those not familiar with this region.

Insofar as shore erosion and the development of beach profiles are concerned, the surface waves interact with sediment in three ways: (1) waves impinging obliquely on the shore create longshore currents and a longshore sand transport, (2) breaking waves throw bottom material into suspension, and (3) the orbital velocities of water wave motion sufficient to lift and move sediment to-and-fro in a wide zone offshore of the breaker zone. The further offshore, the lower the velocity of these bottom orbital motions. By linear theory, at a depth the responding profile would be expected to exceed $2H_5$ in relief. Indeed the historic study of erosion tends to support this suggestion. The responding profiles must have had a relief of about $4H_5$ for this less well established historic change.

Profile response at the other extreme (much less than 5 years) will probably not reach as deep as $2H_5$. The deeper part of the profile may lie unaffected while changes in the upper profile represent a scrambled mixture of responses to waves and water level changes that have occurred both during and prior to the shorter period of observation. Thus, application of the sediment budget prediction on short time scales involves great risk and should be discouraged.

The application of this approach on ocean beaches will be complicated not only by greater difficulties in establishing a sediment budget at most locations, but also (a) by unknown effects that tidal currents and other oceanographic processes have on the closure depth, (b) by the possible differences due to the presence of a broad continental shelf, and (c) by masking of long-term trends by tides and storm surges being superimposed on the much slower submergence resulting from sea level changes and crustal motion. With the longer periods of time necessary for substantial changes in sea level, additional uncertainties arise in evaluating points (a) and (b) above, and in choosing the appropriate wave height, rate of longshore sediment losses, and even the sea level change to best represent long-term net effects. Rates of relative sea level rise over the last century have been measured at many sites. However, rates of change earlier in this most recent epoch of deglaciation probably varied widely from these historic measurements. Future changes are even more problematic.

On ocean coasts, wave periods vary more widely than they do on the Great Lakes. Thus, the effect of wave period should be considered when estimating a closure depth for oceanic sites. Hallermeier[11] developed a Froude number that defines the effect of wave height, wave steepness, and grain size on the initiation of bed motion. Clearly, this parameter would correlate to closure depths better than wave height alone and should be considered in extensions of the sediment balance concept to ocean environments. Hallermeier[12] calculated the depths to which sand is moved by the annual median wave condition at numerous sites but expressed some uncertainty as to whether actual motion extended as deep as indicated for a few of these ocean beaches. An attempt to apply the same criterion to the Lake Michigan study site produces an offshore limit shallower than the observed profile changes. Further refinement therefore seems desirable to firmly establish the critical value of this Froude number associated with the depth of ocean profile response to changes in sea level.

As discussed, additional research in many areas could help clarify how to apply the sediment budget concept to ocean beaches. An unavoidable limitation of this approach will be that the sediment balance concept doesn't even address the question of when the predicted shore response will occur. It merely reveals the horizontal distance the shoreline must *ultimately* move to reestablish the presumed equilibrium profile at its new elevation. The magnitude of the change in water level controls the volume of sand that must be rearranged on the profile. Storms are necessary to provide the energy to accomplish this work and thus control the rate of adjustment. The quantity YZ is an upper limit on the cubic units of sand that must be moved per unit length of beach. For given wave conditions at least the *magnitude of potential* longshore transport rate can be estimated (Chapter 1); the rate of on or offshore transport is even less well established. So even if storminess were predictable, several additional steps would be necessary to calculate the lag time requited for profile equilibration. Meanwhile, empirical data provide some rough guidance: Under not unusual storminess on the Great Lakes it took several years for the rate of shore erosion to drop off following six years of water level increase amounting to 0.2 m. If the water level had risen appreciably slower, the lag time would have been shorter. If shore retreat undermines a steep backshore bluff, several more years of bluff adjustment and revegetation will follow after the beach response is complete.

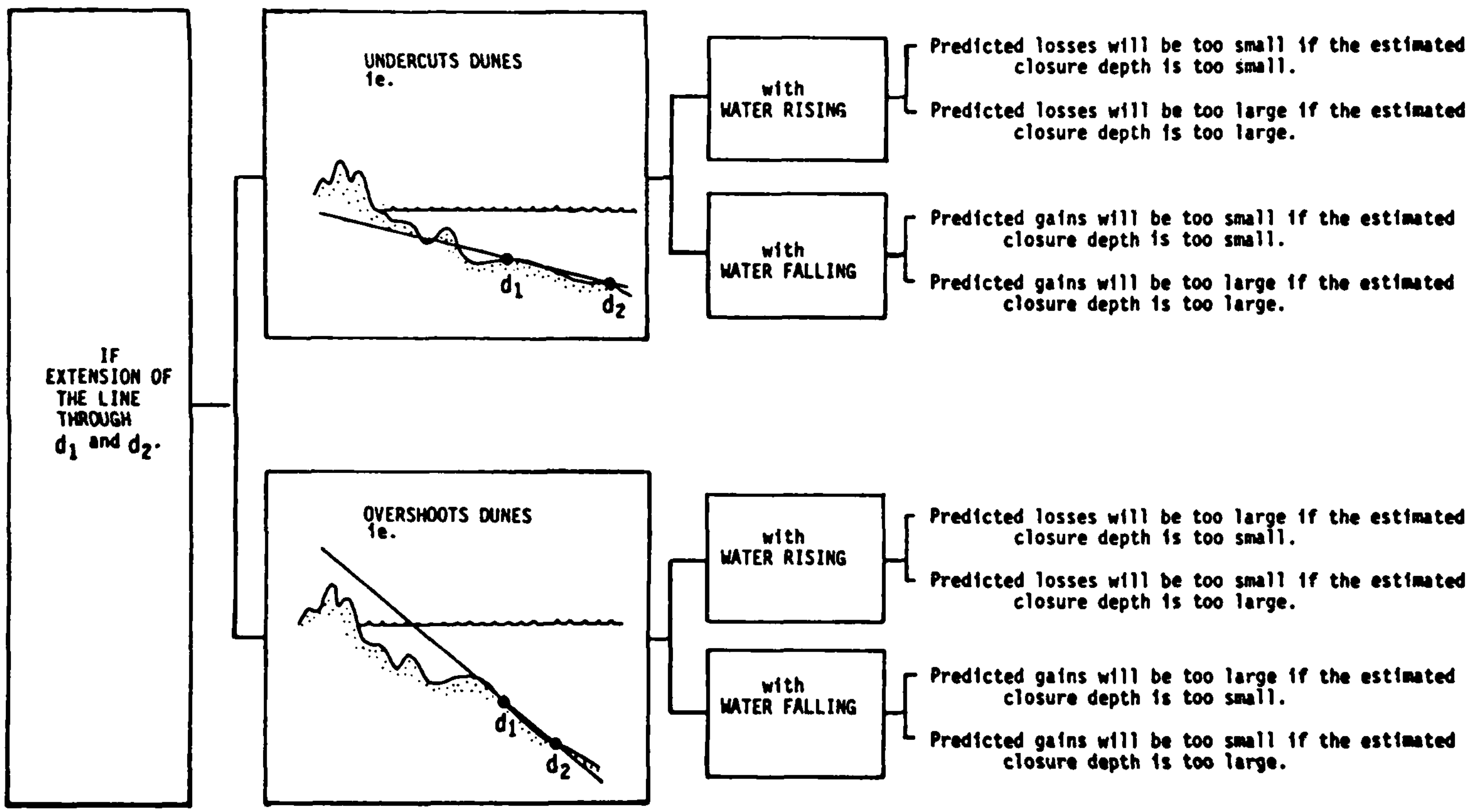

FIGURE 15. Relationships between closure depth and shore response.

CONCLUDING REMARKS

In the absence of other strong evidence as to the correct closure depth, this author suggests "twice the wave height" ($Z \approx 2H_s$) as a rule of thumb to estimate the 5 to 10 year profile response under Great Lakes-like wave conditions; and possibly doubling this value for 100 year estimates. An empirically based critical value of Hallermeier's seaward Froude number may be a better guide on beaches exposed to a wider range of wave periods.

While it is true that confirmation of this approach in the marine environment is lacking (and not likely to be forthcoming due, among other things, to the problem of measuring small, slow changes), there is a saving grace in that the predicted shore response is not very sensitive to moderate errors in the estimation of Z. If Z is too large, there will be a compensatory error in X. In fact, if the bottom slope in the neighborhood of the suspected closure depth is tangent to a line between the closure depth and the highest point of response onshore, then any depth in that neighborhood will provide an identical prediction of shore response (other possibilities are depicted in Figure 15).

Lastly, progradation of the shore in response to falling levels was observed on the Lakes, but the model presented here has not been adequately tested under the conditions of lowered water levels. Such a test could be easily conducted during the next extended period of declining water levels on the Great Lakes.

ACKNOWLEDGMENTS

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