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Areal Variations in Beach Dimensions in the Apostle Islands of Lake Superior

WAYNE N. ENGSTROM*

ON A GLOBAL scale, Davies has shown that areal variations in coastal processes can result in variations in coastal morphology.¹ This observation serves as the hypothesis for this study. Areal variations in both wave conditions and beach dimensions, specifically beach height and width, exist in the Apostle Islands of Lake Superior. Stepwise regression procedures are used to identify the relationships which exist between the beach dimensions and certain wave parameters. This paper provides explanations for those relationships, only some of which have been well documented in earlier studies. The present paper also differs from much of the previous work in that the 39 study beaches are located on 23 islands, whereas existing studies are largely concerned with variations in beach dimensions along a single stretch of coast.

Study Area

The Apostle Islands extend as a group northeastward from the Wisconsin mainland into Lake Superior (Figure 1). A wide variety of wave conditions exists along the beaches of the islands, making the group suitable for this particular study. Most of the islands are composed of sandstone covered with varying thicknesses of glacial

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¹ J. L. Davies, *Geographical Variation in Coastal Development* (New York: Hafner Publishing Company, 1973).

deposits and lacustrine clay. One exception is Long Island, the detached portion of a spit. Island beaches are of two basic types, twelve

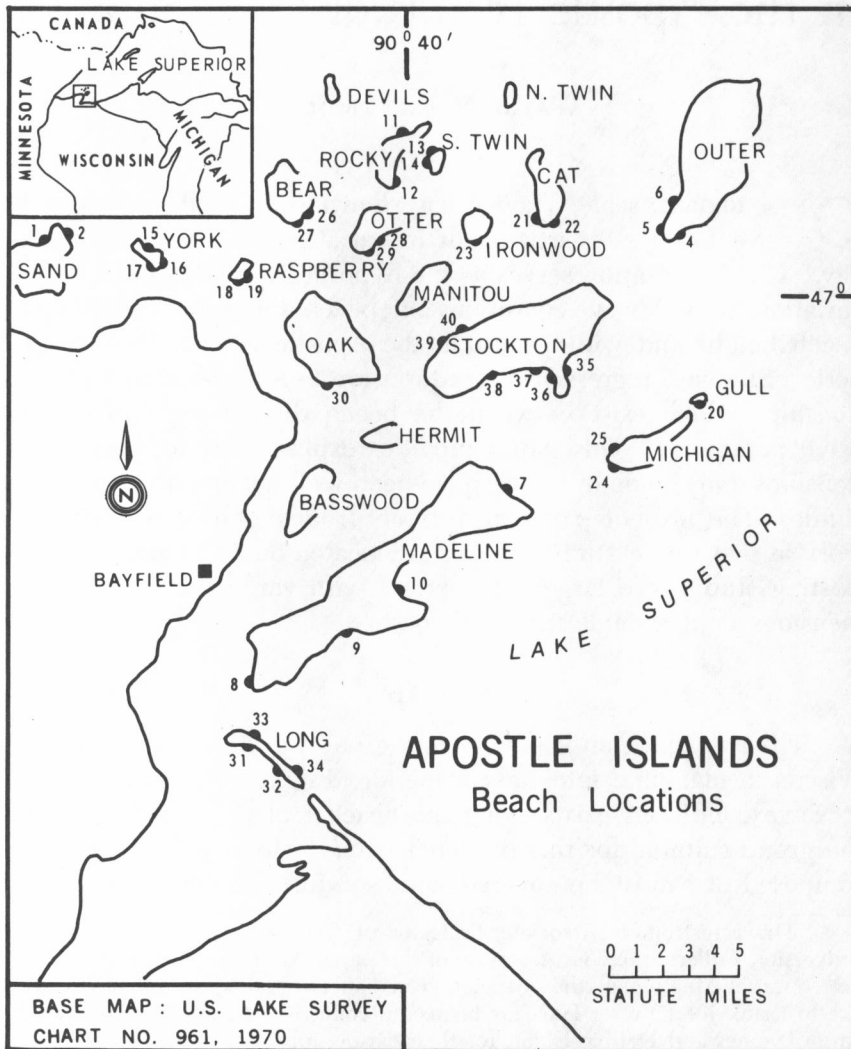


Figure 1. The distribution of study beaches (numbered 1 through 40). An additional beach, originally numbered 3 on Sand Island, has been extensively modified by man and so was deleted from the study.

being of the embayment type with bay-head beaches being most common. The remaining 27 beaches are located on the flanks of spits and cusped forelands.

Waves in the Apostle Islands

It is necessary to estimate the dimensions of waves reaching the beaches because many workers have shown that beach form is genetically associated with certain wave parameters. The S-M-B wave hindcasting procedure was used to hindcast deepwater waves for each of the 39 beaches for two separate periods.² One set of waves (hereafter termed *annual waves*) was hindcast using wind data collected at Duluth, Minnesota, that represent averages for a 10-year period. The second set of waves (hereafter termed *summer waves*) was hindcast using wind data for April through June 1970, provided by the Coast Guard station at Bayfield, Wisconsin. These summer waves provide an estimate of wave conditions during the ice-free period immediately preceding the collection of beach dimension data. Data were collected from the beaches during a three-week period, a circumstance which required that the length of the period for which the summer waves were hindcast be variable because geomorphically significant waves affected the beaches during the collection period.

² The S-M-B wave hindcasting procedure uses a nomogram into which values for wind duration, wind velocity, and fetch for a given situation are entered to hindcast or predict deepwater wave height and wave period. The nomogram is used both by coastal engineers and coastal geomorphologists and is reproduced in several texts and manuals including U. S. Army Coastal Engineering Research Center, *Shore Protection, Planning and Design*, Technical Report No. 4 (Washington: Department of the Army, Corps of Engineers, 1966), p. 19. In the present study, wind durations were assumed to be nonlimiting during the hindcasting procedure because wind duration values were unavailable for the bulk of the data. Only winds in Beaufort force categories 3 and above which had a frequency of occurrence in excess of one-half of one percent were used to hindcast waves. Adjustments for the effects of weather station location on wind velocity and the effects of narrow and irregular fetch widths on effective fetch dimensions were made prior to hindcasting. Also, waves were hindcast for only that portion of the year during which the island group was free of ice. See Wayne Engstrom, "A Method of Predicting Beach Orientation," *Professional Geographer*, Vol. 25 (1973), p. 13.

Estimation of both long-term (annual) and short-term (summer) waves is necessary because beach dimensions largely adjusted to the short-term waves are more dynamic than beach dimensions mainly adjusted to the long-term waves. Additionally, all beach dimensions on small beaches may be adjusted to the short-term waves and all the beach dimensions on large beaches may be adjusted to the long-term waves.

A large array of annual and summer waves was generated by the hindcasting procedures. This array proved to be too bulky for all but the most lengthy analysis, so both annual and summer waves were sorted out by magnitude and frequency analysis.³ The wave heights and wave periods predicted by the S-M-B hindcasting procedure were used to derive a measure of wave work after the wave periods were used to obtain wave lengths. The wave-work value, calculated for all waves hindcasted, is given by the product of the square of wave height and wave length when multiplied by the percentage frequency of the wave-generating wind as shown below:⁴

$$WW = P(H^2 \times L)$$

where

WW = wave-work value,

P = percentage frequency of the wave-generating wind,

H = deepwater wave height, and

L = deepwater wave length.

The height, length, steepness, angle of approach, and the wave-work value of the wave identified as having the largest wave-work value for a beach for both the annual and summer periods were used as process variables in the statistical analysis. This particular set of wave parameters is theorized to be geomorphically dominant on a given beach for the specified period.⁵ Other variables derived from the hindcasted wave data include the wave-work sums for the two

³ See M. Gordon Wolman and John P. Miller, "Magnitude and Frequency of Forces in Geomorphic Processes," *Journal of Geology*, Vol. 68 (1960), pp. 54-74.

⁴ Engstrom, p. 13.

⁵ Wayne N. Engstrom, "Beach Foreshore Sedimentology and Morphology in the Apostle Islands of Northern Wisconsin," *Journal of Sedimentary Petrology*, Vol. 44 (1974), p. 192.

periods, for the dominant azimuth of wave approach for the two periods, and for selected Beaufort force categories.

Selected for illustration is the distribution of the wave-work sums associated with all the annual waves generated by Beaufort force four winds for a given beach (Figure 2). On most beaches this set of annual waves, as compared to those associated with the other Beaufort force categories, did the greatest amount of work on the beach, using the wave-work sums as the criterion. Wave-work levels are greater on the lakeward periphery of the island group and diminish rather systematically toward the mainland. This trend reflects a similar regional trend in the fetch available to generate waves. Exceptions are the unusually large values at beaches at the ends of inter-island channels which are open to the main body of the lake.

Foreshore width is an additional process variable which emerged from the statistical analysis, showing a significant correlation with beach height and width. Foreshore width was measured normal to the beach strike in the field. This variable provides a rough approximation of the amount of wave energy actually reaching the beaches, which may differ markedly from energy values calculated from the dimensions of unrefracted deepwater waves. Several investigators have shown that a positive relationship exists between foreshore width and wave energy which indicates that wide foreshores record high energy conditions and narrower foreshores record lower energy conditions.⁶ It is necessary to assume that the distance traveled inland by especially vigorous swash is not artificially limited by foredunes, coastal cliffs, or other topographic barriers.⁷ Additionally, the mean grain size of the foreshore sediment was included in all regression equations in order to control statistically for the effect of mean grain size on the width of the foreshore. Coarse mean grain

⁶ Cuchlaine A. M. King, *Beaches and Coasts*, 2nd ed. (New York: St. Martin's Press, 1972), p. 321; Roger N. Dubois, "Seasonal Variation of a Limnic Beach," *Bulletin, Geological Society of America*, Vol. 84 (1973), p. 1821; A. T. Williams, "Phase Changes in Beach Profiles and Beach Sediments," *Zeitschrift für Geomorphologie*, Vol. 18 (1974), p. 17.

⁷ The "receptive shore" concept of Cooper, although applied to the growth and maintenance of coastal sand dunes, expresses much the same idea. See William S. Cooper, *Coastal Sand Dunes of Washington and Oregon*, Memoir 72, (Boulder, Colorado: Geological Society of America, 1958), p. 86.

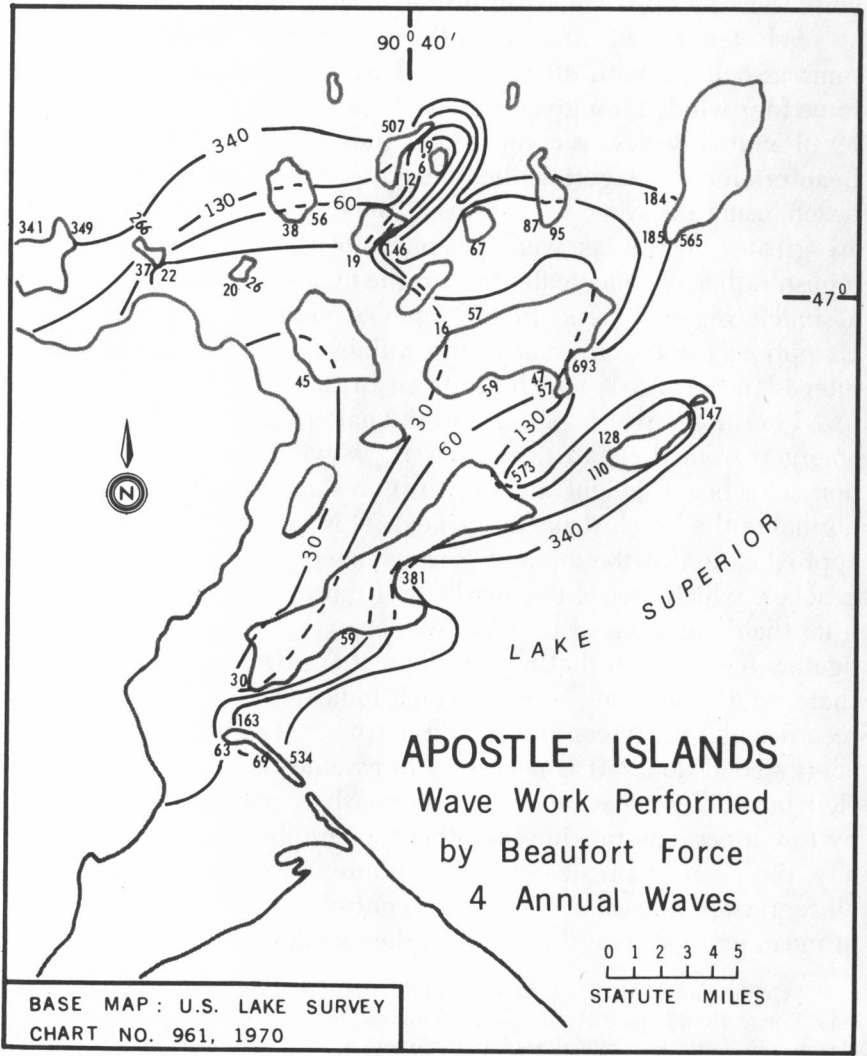


Figure 2. The distribution of annual wave-work values associated with waves generated by all Beaufort force 4 winds. Values shown for each beach represent the sum of all wave-work values for all possible azimuths of wave approach.

sizes reduce swash volume which in turn reduces foreshore width, whereas the opposite effect results from fine mean grain sizes. In subsequent studies it may be useful to further refine this variable by considering the effect that foreshore slope and other variables have on foreshore width.⁸

Beach Height and Beach Width

Beach height and beach width at each sampling station were measured in the field during June 1970, using elementary surveying tools.⁹ It is important to complete measurements of this type in as brief a period as possible because seasonal variations in lake level on the Great Lakes can markedly affect beach height and width. Dubois' work on Lake Michigan, for example, has shown that a one-foot (.3 m) rise in lake level can reduce beach heights by the same amount and diminish beach widths by 17 feet (5.2 m).¹⁰

Beach height is defined as the vertical distance between the lakeward edge of the foreshore and the landward edge of the active beach. The landward edge of the active beach is taken to be the lower limit of vegetation on the beach. Beach width is defined as the horizontal distance between these two points. Only the dimensions of the unvegetated, mainly subaerial portion of the beach profile are being investigated. Aeolian and subaqueous beach topography has

⁸ See, for example, C. J. Sonu and D. S. McArthur, "Wave Run-up on a Natural Beach, North Carolina," (*abs.*) *Special Paper*, Geological Society of America, No. 115 (1968), pp. 500-501; W. F. Tanner and F. W. Stapor, "Precise Control of Wave Run-up in Beach Ridge Construction," *Zeitschrift für Geomorphologie*, Vol. 16 (1972), pp. 395-396; and W. Harrison, "Prediction of Beach Changes," *Progress in Geography*, Vol. 2 (1970), pp. 226-227.

⁹ Samples of beach sediment were also collected from the upper foreshore at each sampling station at the same time the beach dimensions were measured. All samples were split into sand and gravel fractions. The sand fraction was reduced to a 15-20 gram split which was subsequently sieved in an Allen-Bradley Sonic Sifter with the sieves spaced $\frac{1}{4}$ phi apart. Averaging 9 percent of the sediment sample, the entire gravel fraction was measured manually at $\frac{1}{4}$ phi intervals. The results of both the sand and gravel analyses were combined and then the method of moments was used to determine the various grain-size parameters. The mean grain size was 0.67 phi (0.63 mm) for all the samples collected. See Engstrom (1974), p. 191.

¹⁰ Dubois, p. 1822.

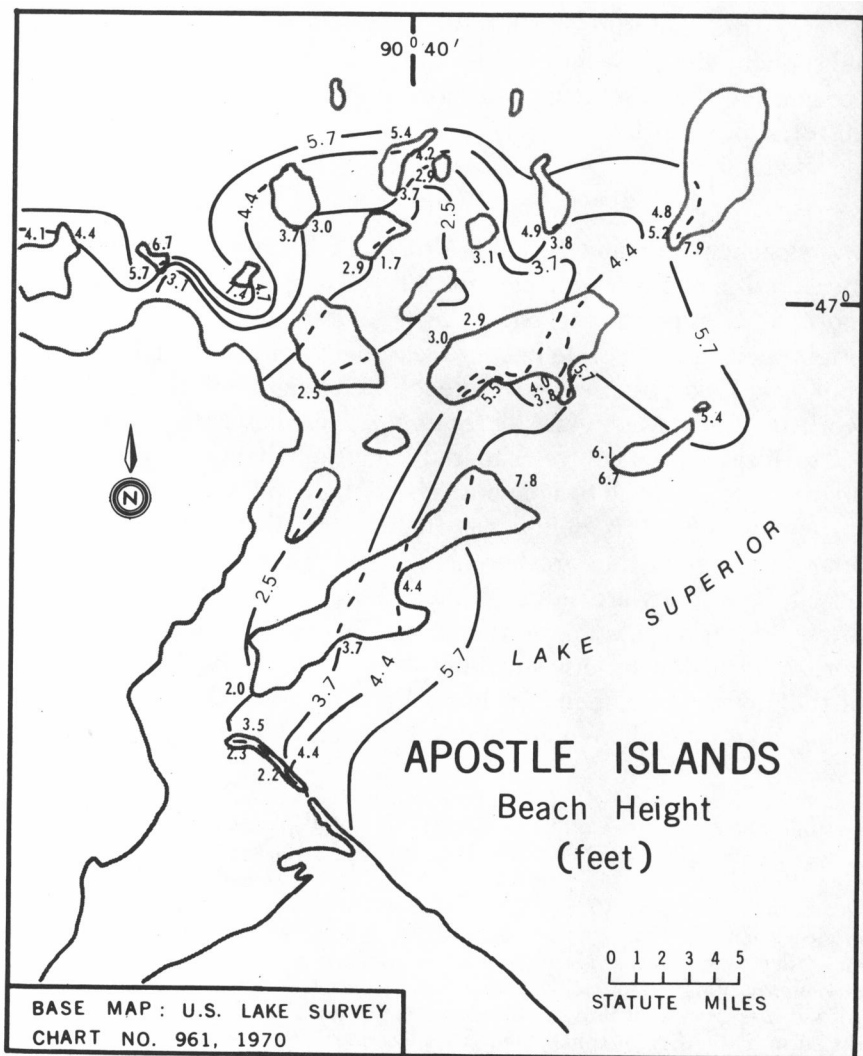


Figure 3. The distribution of beach heights. Values shown for each beach represent the mean of several individual measurements.

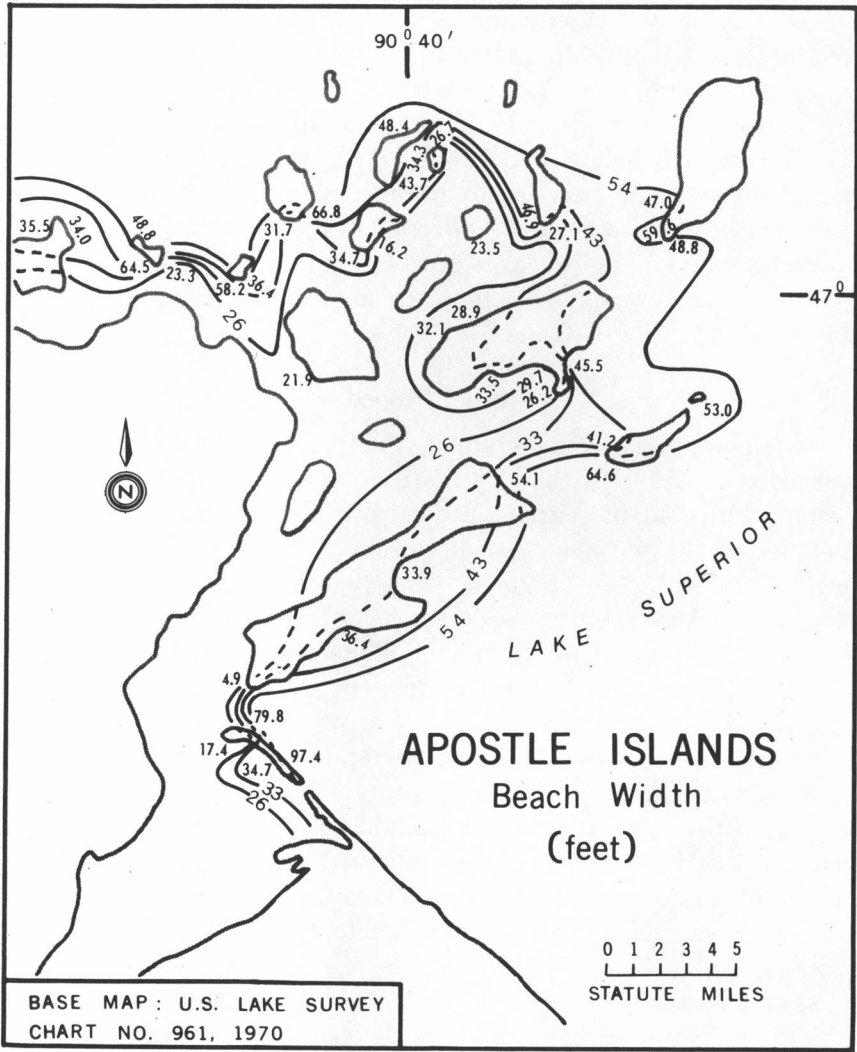


Figure 4. The distribution of beach widths. Values shown for each beach represent the mean of several individual measurements.

been excluded from consideration by design. Height and width measurements were made for every 1,000 feet (305 m) of beach length, from which average beach height and width values for each beach were calculated. The average height for all beaches is four and one-half feet (1.4 m) and the average width is 44.2 feet (13.5 m).

Both beach height and beach width vary considerably within the island group but show much the same regional trend as do the wave-work values in Figure 2. Specifically, higher and wider beaches are to be found along the lakeward periphery of the islands, whereas lower and narrower beaches typically are located closer to or facing the mainland (Figures 3 and 4).

Statistical Procedures

Stepwise regression, employing the forward selection procedure, was used to examine the relationships between beach height and beach width and the various process variables. Normality transformations of the variable distributions were made where required prior to the initiation of the stepwise regression procedure. Hauser has described stepwise regression as being essentially a search procedure designed to identify which independent variables have the strongest relationship with the dependent variable, and for that reason the stepwise regression procedure was adopted.¹¹ Draper and Smith provide a useful discussion of stepwise regression and related procedures and conclude that the procedure used here should yield the best subset of independent variables.¹² In this approach, independent variables are added and may later be removed from the regression equation on the basis of the significance levels of the partial correlation coefficients with the dependent variable. A significance level of 0.10 was used for both inclusion and exclusion from the regression equation.

Three stepwise regression models were used. These included a model using data from all beaches (all beaches model), a model

¹¹ D. P. Hauser, "Some Problems in the Use of Stepwise Regression Techniques in Geographical Research," *Canadian Geographer*, Vol. 18 (1974), p. 149.

¹² N. R. Draper and H. Smith, *Applied Regression Analysis* (New York: John Wiley and Sons, Inc., 1966), pp. 169-172.

using data from only spit and cusped foreland beaches (spit beach model), and a model using data only from embayment beaches (embayment beach model). Inspection of the relevant correlation matrices shows that considerable collinearity exists among several of the wave-work variables derived from the hindcasted wave dimensions, and multicollinearity must also be suspected. Regression coefficient instability, particularly in terms of sign change, is known to result from collinearity and multicollinearity.¹³ Accordingly, geomorphic interpretation of the wave-work variables appearing in final regression equations will be made in light of the sign of the simple correlation coefficient between the wave-work variable and the dependent variable, rather than the sign of the partial correlation coefficient. Only those independent variables whose partial correlation coefficients are significant at the 0.05 level will be discussed.

Beach Height

Stepwise regression analysis in which beach height is the dependent variable indicates that the largest group of independent variables appearing in the final regression equations of the three models consists of variables which are measures of wave energy. These include foreshore width in addition to several wave-work variables (Table 1). In all cases, the relevant correlation coefficient between the wave energy variable and beach height is positive, indicating that beaches heighten as wave energy levels increase. These results are consistent with the distribution of wave-work values and beach height values (Figures 2 and 3).

An abundant literature demonstrates that beach height and related measures such as swash bar height, beach ridge height, and berm height generally increase in magnitude as the wave energy level increases. Wave energy level is often specified in terms of wave height in much of the previous work. Early wave tank experiments by Bagnold indicate that beach height is directly proportional to the height of the formative waves.¹⁴ Similar wave tank experiments

¹³ Hauser, p. 151.

¹⁴ R. A. Bagnold, "Beach Formation by Waves; Some Model-Experiments in a Wave Tank," *Journal of the Institute of Civil Engineers*, Vol. 15 (1940), p. 38.

Table 1. Stepwise Regression Analysis of Beach Height

Model	N	R	Variable	Simple correlation with beach height	Partial correlation coefficient	Standardized partial regression coefficient
All beaches	39	0.82*	X ₁ (mean grain size)	-0.15	-0.52*	-0.41
			X ₂ (foreshore width)	0.42*	0.60*	0.52
			X ₃ (log of the sum of all wave-work values for the dominant azimuth of annual wave approach)	0.31	-0.65*	-3.67
			X ₄ (log of wave-work value of the most important work performing annual wave)**	0.37*	0.54*	2.91
			X ₅ (log of the sum of all annual wave-work values)	0.40*	0.38*	1.12
			X ₆ (steepness of most important work performing summer wave)	-0.07	0.32	0.24
Spit beach	27	0.55*	X ₁ (mean grain size)	-0.28	-0.49*	-0.53
			X ₂ (foreshore width)	0.29	0.49*	0.54
Embayment beach	12	0.69	X ₁ (mean grain size)	-0.13	-0.18	-0.13
			X ₂ (angle of deepwater wave approach of the most important work performing summer wave)	-0.68*	-0.69*	-0.68

SOURCE: Calculated by author.
* Significant at the 0.05 level.
** The phrase "most important work performing . . . wave" refers to the specific wave which has the largest wave-work value for the indicated period.

conducted later by King show that swash bar height increases as wave height increases.¹⁵ Bascom has shown that in nature the height of berms on sand beaches is a positive function of the height of the refracted wave which molds the beach.¹⁶ Davies notes that the height to which a beach is built depends entirely on the height of the waves which build it.¹⁷ Work by Tanner and Stapor has shown that this relationship also applies to beach ridges.¹⁸

Beach height appears to increase as wave energy increases because the more vigorous swash generated by such waves is able to travel farther inland, reaching higher and normally unsaturated portions of the beach profile where deposition occurs. Such deposition may take place even during stormy episodes of wave attack despite an accompanying reduction in beach width because of erosion on the lower part of the beach profile.¹⁹ Even swash traveling only to the berm crest is capable of promoting the upward growth of the beach through deposition because the crest is seldom saturated and percolation losses are correspondingly great.²⁰ Swash washing over the berm crest cannot return lakeward as erosive backwash and the resulting washover deposits can increase beach elevations as Psuty has reported.²¹

Mean grain size constitutes one of the remaining independent variables appearing in the final beach height regression equations (Table 1). The partial correlation coefficient between mean grain size in phi units and beach height is negative in all instances. This shows that higher beaches are linked with coarser foreshore sediment and lower beaches with finer foreshore sediment. Assuming

¹⁵ King, p. 321.

¹⁶ Willard Bascom, *Waves and Beaches* (Garden City, New York: Doubleday and Company, 1964), p. 199.

¹⁷ Davies, p. 119.

¹⁸ Tanner and Stapor, pp. 398-399.

¹⁹ See, for example, Williams, p. 29; Norbert P. Psuty, *The Geomorphology of Beach Ridges in Tabasco, Mexico*, Coastal Studies Series No. 18, (Baton Rouge: Louisiana State University Press, 1967), p. 17; and J. P. Coakley, W. Haras, and N. Freeman, "The Effects of Storm Surge on Beach Erosion, Point Pelee," *Proceedings, Sixteenth Conference on Great Lakes Research* (1973), p. 383.

²⁰ Tanner and Stapor, p. 397.

²¹ Psuty, p. 28.

that the mean grain size of the foreshore sediment is representative of all the beach sediment, this relationship may be partly explained by Davies' observation that pebbles can be thrown some distance past the limit of swash and hence out of the reach of backwash.²² Gravel-sized material constitutes, on the average, 9 percent of the foreshore sediment. More importantly, however, coarse beach sediment promotes greater percolation of swash and a corresponding greater reduction in the strength of backwash than does fine beach sediment. These circumstances both encourage deposition and the construction of relatively high beaches.

The angle of deepwater summer wave approach has an effect on beach height, at least in the case of the embayment beaches (Table 1). The angle of wave approach is expressed as the angular difference between the azimuth of deepwater wave approach and the azimuth of beach orientation. The orientation of a beach is given by a perpendicular to the beach strike. The negative sign of this relationship indicates that beaches increase in height as the angular difference between the azimuths of wave approach and beach orientation diminishes. Under these conditions, swash travels directly up the beach, reaching the higher and drier parts of the beach profile where deposition is encouraged. When waves approach the beach at a greater angle to the azimuth of beach orientation, swash travels more parallel to the beach strike, being confined to the lower and more saturated parts of the beach profile where deposition is not encouraged. Some of the linkages between angle of wave approach, direction and distance of swash travel, and beach height have been noted by other workers. Lewis observed that the highest beach ridges on a shingle beach were always built by the waves approaching directly onshore.²³ Dolan has argued that increased angles of wave incidence should be associated with a reduction in beach

²² Davies, p. 119, and also J. L. Davies, "The Importance of Cut and Fill in the Development of Sand Beach Ridges," *Australian Journal of Science*, Vol. 20 (1957), p. 107.

²³ W. V. Lewis, "The Effect of Wave Incidence on the Configuration of a Shingle Beach," *Geographical Journal*, Vol. 78 (1931), p. 134.

thickness (height).²⁴ Harrison has stated that the distance that swash travels up the foreshore increases as the crests of the breaking waves more nearly parallel the shoreline.²⁵

Beach Width

The analysis suggests that the width of the beaches in the study area is primarily controlled by variations in wave energy, with increases in wave energy being associated with increases in beach width (Table 2). Visual comparison of the distribution of both wave-work values and beach width values leads to the same conclusion because both sets of values are greatest on the more exposed, outer beaches of the island group and then decline toward the more protected beaches nearer to and/or facing the mainland (Figures 2 and 4). Similarly, Dubois reports a positive correlation between breakpoint wave height and beach width for a stretch of Lake Michigan beach.²⁶

Some of the arguments expressed earlier concerning the nature of the association between beach height and wave energy may be logically extended to the wave energy/beach width association. Vigorous swash generated by high energy waves travels far inland where beach sediment is deposited. Beach widening in the island group would seem, therefore, to involve accretion at the landward edge of the beach. Simultaneous lakeward growth of the beach also can occur as wave energy levels increase if the waves are constructive in character, a circumstance which appears likely given the positive sign of the relationship.

Sediment supply, although not measured directly in this study, has been recognized as playing an important role in controlling beach width.²⁷ Sediment supply is likely the greatest for beaches positioned on the flanks of those relatively large spits and cusped forelands extending from islands located on the lakeward periphery of the island group where relatively strong longshore currents are

²⁴ Robert Dolan, "Beach Changes on the Outer Banks of North Carolina," *Annals of the Association of American Geographers*, Vol. 56 (1966), p. 708.

²⁵ Harrison, pp. 223-224.

²⁶ Dubois, p. 1822.

²⁷ Davies (1973), pp. 119-120.

Table 2. Stepwise Regression Analysis of Beach Width

Model	N	R	Variable	Simple correlation with beach width	Partial correlation coefficient	Standardized partial regression coefficient
All beaches	39	0.45*	X ₁ (mean grain size)	0.13	0.12	0.10
			X ₂ (log of wave-work value of the most important work performing annual wave)**	0.45*	0.44*	0.44
Spit beach	27	0.73*	X ₁ (mean grain size)	0.23	-0.16	-0.13
			X ₂ (foreshore width)	0.61*	0.56*	0.54
			X ₃ (log of the sum of all summer wave-work values)	0.55*	0.50*	0.42
Embayment beach	12	0.99*	X ₁ (mean grain size)	-0.39	0.46	0.11
			X ₂ (sum of all annual wave-work values)	0.78*	0.93*	7.16
			X ₃ (foreshore width)	0.42	0.95*	0.49
			X ₄ (sum of all annual wave-work values for waves generated by Beaufort force 4 winds)	0.75*	-0.92*	-5.82
			X ₅ (sum of all summer wave-work values)	0.65*	-0.74*	-0.55

SOURCE: Calculated by author.
* Significant at the 0.05 level.
** The phrase "most important work performing . . . wave" refers to the specific wave which has the largest wave-work value for the indicated period.

depositing sediments. Beaches located in this situation include those along Outer, Michigan, Bear, Raspberry, and York Island cusped forelands in addition to the two beaches on the northern side of Long Island (Figure 4). Beaches in such situations are characterized by high wave energy levels and so perhaps the positive wave energy/beach width relationship may be partly linked to rapid rates of progradation caused by excessive longshore current sedimentation. Delivery of a large amount of sediment to the shoreline does not insure that a wide beach will develop, because a minimum wave energy level must be achieved before beach construction is initiated.²⁸ In conclusion, even the largest waves that are geomorphically dominant on the beaches may be fundamentally constructive in nature and, particularly when supplied by longshore currents with much sediment, can build relatively wide beaches.

Conclusions

Some conclusions may be drawn about areal patterns in beach height and beach width within the island group, but continued inquiry is needed because the statistical analysis suffers from collinearity and possibly multicollinearity among some independent variables and considerable unexplained variation in beach height and width in several models. Collinearity and multicollinearity, which can lead to interpretative difficulties, may be avoided through the use of additional procedures, such as principal components analysis, that have been suggested by Hauser.²⁹

Both the statistical analysis and a visual comparison of the appropriate maps show that low, narrow beaches are associated with low wave energy levels characteristic of protected locations facing or nearer the mainland. Beaches both heighten and widen as wave energy levels increase toward the open lake, reaching maximum values in more exposed locations. Coarse beach sediment and small

²⁸ William F. Tanner and John D. Bates, "Submerged Beach on a Zero-Energy Coast," *Southeastern Geology*, Vol. 7 (1965), p. 21.

²⁹ Hauser, pp. 152-153.

angles of wave approach also encourage increases in beach height. Beach width is controlled largely by wave energy and, to some partly specified extent, by sediment supply.