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THE VALUE OF BARRIER ISLANDS: 1. MITIGATION OF LOCALLY-GENERATED WIND-WAVE ATTACK ON THE MAINLAND

By

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ABSTRACT

The value of barrier islands for protecting the mainland shoreline from locally-generated wave attack is evaluated through the use of the shallow water wave prediction model HISWA. Critical to this work is HISWA's ability to simultaneously generate and dissipate waves through wind stress and wave breaking processes, respectively. A series of tests with an idealized barrier/bay configuration is used to define the conditions in which the removal of a barrier island, as through erosion, will result in a significantly increased wave height at the mainland shoreline. Due to the depth-limited nature of waves in shallow bays, the results are a complex function of the wind speed, bay width, and bay depth. In general, barriers fronting wide, shallow bays have little potential to protect the mainland shoreline from wind-wave attack, while those associated with narrow, deep bays have a large potential. For intermediate conditions, the results may depend on a wide range of complicating factors which are discussed, though not quantitatively accounted for in the current treatment.

INTRODUCTION

In terms of their protection of mainland shorelines, wetlands, and estuarine habitats, the value of barrier islands is widely considered nearly self-evident. Numerous papers cite the impending loss of a barrier island as an almost certain predecessor to increased erosion of mainland shorelines or degradation of biologically important estuarine environments (e.g. Leatherman et al., 1987; Sallenger et al., 1987; McBride et al., 1992; Penland et al., 1992; Basco, 1992). The most commonly evoked problems related to the removal of a barrier island (through erosion) include increased wave energy and storm surge at the mainland shoreline, and increased estuarine salinity. Nevertheless, few, if any, studies have attempted to quantify the negative effects of barrier island erosion in such a way that the value of the barrier island may be assessed.

Quantitative information of this nature is needed for many eroding coastal areas of the U.S.A. and other regions throughout the world. For example, along the barrier island coast of Louisiana, a series of rapidly disintegrating barrier islands front an extensive system of bays and marshes. Without human intervention, many of these islands are predicted to disappear early in the 21st century (McBride et al., 1992). A critical need exists within the State of Louisiana to understand the impacts of this erosion on the physical and biological environment, thereby enabling better decisions on tactics for mitigating the extreme rates of wetlands loss suffered in the Louisiana deltaic plain.

This paper addresses one component vital to assessing the value of barrier islands: the role of barrier islands in sheltering the mainland shoreline from wave attack. Although at first glance this may seem perhaps the most obvious value of barrier islands, the depth-limited nature of wave height in shallow water (Thornton and Guza, 1982; Sallenger and Holman, 1985) will clearly result in some conditions, such as with an extremely wide and shallow bay, in which the removal of a barrier island will have little effect on the wave energy impacting the mainland shoreline. The purpose of this study is to quantitatively examine the range of those conditions that define the role of barrier islands in mitigating wave energy reaching the mainland shoreline.

First, we describe the numerical wave prediction model selected for this work and define the simplifying assumptions adopted in order to permit a generalized, non-site-specific result. Multiple model runs are then presented in a simple nomograph which generalizes the results for most barrier/bay configurations. The results are then discussed in light of complicating factors that must be considered for a rigorous application of the results to a specific barrier/bay system.

HISWA MODEL

The prediction of wave heights in a barrier/bay system requires, at the least, a model that accounts for the processes of shallow water wave generation by wind, propagation over arbitrary topography, and energy dissipation by breaking and bottom friction. The approaches employed by most wave prediction models make the simultaneous incorporation of all these processes problematic. For example, solutions of the mild slope equation have lead to a recent revolution in combined refraction-diffraction modeling of single frequency waves (Berkoff, 1972; Radder, 1979; Ebersole, 1985; Kirby, 1986; among many others). Although this type of modeling has recently been extended to include a directional spectrum representation (Isobe, 1987; Panchang et al., 1990), none have incorporated even a simple parameterization of wind-induced wave growth with dissipation through both bottom friction and shallow-water breaking.

A model that does incorporate these effects, albeit parametrically, is the directional wave generation, propagation, and dissipation model HISWA (HIndcasting Shallow water WAves, Holthuijsen et al., 1989). HISWA computes wave heights on a rectangular grid by solving a wave action balance equation of the form

$$\frac{\partial}{\partial x}C_x A + \frac{\partial}{\partial y}C_y A + \frac{\partial}{\partial \theta}C_\theta A = T \tag{1}$$

where A is the action density defined as the energy density normalized by the relative frequency (wave frequency modified by current), C_x and C_y represent the propagation speeds in the x and y directions respectively, C_θ represents refraction (rate of change in wave direction, θ), and T represents a source term for gains from wind generation and loss through friction and breaking. Propagation thus includes shoaling and refraction due to both bottom topography and steady currents; wave diffraction is not modeled. Wave generation by wind is handled through an empirical source term that is calibrated to approximate the wave growth curves of the Shore Protection Manual (U.S. Army Corps of Engineers, 1984). Waves are dissipated through both bottom friction following a quadratic friction law (e.g., Putnam and Johnson, 1949) and through wave breaking following the approach of Battjes and Janssen (1979).

The model has been tested under a variety of field and laboratory conditions, with generally favorable results (Dingemans et al., 1987; Booij et al., 1988; Holthuijsen et al., 1989; Vogel et al., 1989; Den Adel et al., 1991). The test with the most application to the work presented here was conducted by Holthuijsen et al. (1989), who found agreement to about 10% between modeled and measured wave heights across a shallow nearshore shoal using default HISWA parameters. These model default parameters are used here without further verification.

PROBLEM DEFINITION

In its most simplified form, a barrier island system consists of a shoreface profile leading up to the subaerial barrier, backed by a lagoon of a certain constant depth and a mainland shoreline (Fig. 1b). Waves entering the system from offshore are entirely blocked by the subaerial barrier, but are regenerated in the bay in the presence of onshore directed wind (Fig. 1a). Key to this study is the prediction that in the lee of the barrier, wave regeneration occurs over a finite width of bay; that is, a certain fetch is required for the waves to reach a maximum height as a function of the limited bay water depth. Also, at higher wind speeds the fetch required to reach this wave height maximum is reduced.

Now consider the most simplified case of barrier island erosion—total removal of the barrier leaving a shallow extension of the bay (Fig. 1b). Clearly, the erosion of most barriers will not follow this idealized case, but will erode through shoreface retreat, inlet breaching and expansion, etc. However, the simplified case in Fig. 1b represents an erosional end-member through which the effect of barrier island removal alone may be quantified. The consequences of other modes of barrier island erosion will be explored in the discussion section below.

Waves entering this eroded barrier profile will clearly undergo a different transformation than in the barrier-present case. Breaking still occurs over what remains of the shoreline and nearshore profile; however, the wave height now gradually decreases into the shallow bay depths until an energy balance is reached between the dissipative processes of breaking and bottom friction and the generative process of wind stress. At this point waves have the same stable bay wave height as in the barrier-present case (Fig. 1a).

A comparison between the barrier and no-barrier wave height profiles reveals a zone in which the wave height is significantly higher in the no-barrier case (Fig. 1a). This zone, referred to as the "critical bay width" or W_{crit}, is defined here by at least a 10% increase in wave height from the barrier case to the no-barrier case. From another perspective, the mainland shoreline will experience at least a 10% increase in wave height if the bay width, W_b, is narrower than W_{crit}, whereas when $W_b > W_{crit}$ the mainland shoreline will experience no significant increase in wave height due to barrier island removal. (The use of a 10% criteria is arbitrary; as described in the discussion section below, varying this criteria will affect W_{crit} in a predictable manner.)

The problem is now reduced to one of finding the dependence of W_{crit} upon variables such as the wind speed, U_{10}, and the bay depth, h_b. In the one-dimensional profile case considered here, HISWA is simplified to the first and last terms of eqn. (1), with the only relevant processes being shoaling, breaking, bottom friction, and wind-generation. For all model runs presented below, HISWA is used in this 1-D form with a cross-shore grid spacing of 100 m. Bay depths, h_b, vary between 1.0 and 5.0 m, with wind velocities at 10 m elevation, U_{10}, ranging between 5 and 60 m/s, all in a shore-normal orientation. The input significant wave height, H_s, and mean period, $\overline{T}$, at the seaward model boundary (i.e. Fig. 1, distance = 0) are given by eqns. 3-39 and 3-40 of the Shore Protection Manual (U.S. Army Corps of Engineers, 1984). These input wave characteristics, shown in Fig. 2, are used in order to provide a boundary condition consistent with the model formulation. However, the exact value at the boundary has little influence on W_{crit} due to H_s limitations in the shallow nearshore.

The average wave period, $\overline{T}$, is allowed to vary as a function of breaking and bottom friction (a HISWA option), which allows $\overline{T}$ in the no-barrier case to decrease into the shallow bay depths. This is supported by limited field evidence (Holthuijsen et al., 1989) showing that when the waves are locally generated, longer period waves entering from offshore are replaced by shorter period waves in shallow areas. Allowing $\overline{T}$ to vary results in a near-match between the barrier and no-barrier wave periods by the time waves have reached a distance equal to W_{crit}. Without this $\overline{T}$ variation, the waves in the no-barrier case never attain the same short period and stable height predicted in the barrier-present case.

The HISWA parameter controlling the directional spread of the waves is set to $ms = 2.0$, giving the wide directional spread characteristic of locally-generated wind waves. However, this parameter has no influence on the results due the 1-D run mode used and is reported here only for completeness. All other user-variable parameters in the model, including the breaking and friction coefficients, are left as the default values as described by Holthuijsen et al. (1989).

A problem exists in the current version of HISWA concerning the regeneration of waves in the bay for the barrier island case. If the first wetted grid node ($h > 0$) landward of the barrier has, through chance, a very small water depth of O(0.1 m), HISWA overpredicts H_s at this node in apparent disregard for breaking limitations. At the next grid node in the direction of wave travel, H_s is reduced and a smooth growth curve representing wind generation of waves ensues. This initial overprediction was eliminated in this study by shifting the grid over the bottom (slope $\tan\beta = 0.005$ on the bay side of the barrier island) until the first wetted grid node had $h = 0.38$ m. Smooth growth curves as in Fig. 1 resulted; the model still has an inherent problem with wave height prediction at the first wetted grid node, but it is judged not to affect the results presented here.

RESULTS

The results for $h_b = 2.5$ m are given in Fig. 3, which shows the critical bay width, W_{crit}, as a function of the wind speed, U_{10}. The resulting curve defines two regions: an area below the curve in which the mainland shoreline would experience a significant increase in H_s (>10%) if the barrier island were removed, and an area above the curve in which the increase in H_s would be minimal (<10%) if the barrier island were removed. This plot can be applied to a barrier/bay system with $h_b = 2.5$ m by drawing a horizontal line across the curve at a level representing the bay's width. For a given bay width, the mainland shoreline is protected at wind speeds up to the line's intersections with the W_{crit} curve, while at higher U_{10} values the barrier island provides no protection.

An interesting though perhaps counter-intuitive result from Fig. 3 is that barrier islands protect the mainland shoreline from wave attack at lower wind speeds, while during higher winds the barrier island provides minimal protection. As it is the stronger winds that are generally associated with erosional events, this limits barrier islands's value in terms of wave height mitigation. However, the break in slope of the W_{crit} curve, at least for the $h_b = 2.5$ m results in Fig. 3, divides bays into two classes: bays with $W_b >\sim 5$ km, for which barriers afford protection only up to $U_{10} \approx 10$ m/s (a minor storm), and bays with $W_b <\sim 5$ km, for which barriers are increasingly protective for storms up to hurricane force.

The results for bay depths ranging from $h_b = 1.0$ to 5.0 m are shown in Fig. 4. Now the division between conditions in which the barrier island protects the mainland shoreline and conditions in which it does not is defined by a family of curves. Not surprisingly, the overall result is that with a deeper bay (larger h_b) the region of barrier island protection expands. The critical bay width increases because both wave regeneration in the barrier case and wave decay in the no-barrier case require a larger travel distance to reach a stable value.

Several features of Fig. 4 are somewhat perplexing and should be mentioned here. First, the W_{crit} values for $h_b = 4.5$ and 5.0 m at $U_{10} = 5$ m/s have unexpectedly low values, matching the $h_b = 4.0$ m W_{crit} value at the same wind speed. An examination of plots similar to Fig. 1 reveals that for this combination of low U_{10} and high h_b the wave height in the bay is not depth-limited. Thus the wave height in the no-barrier case does not decay into the zone with $h = h_b$; W_{crit} is reduced because the wave height in the barrier case reaches to within 10% of the no-barrier case in a shorter distance. (Only the barrier case H_s curve must converge to the stable bay value.)

Another notable feature of Fig. 4 is the minimum in the W_{crit} curves for $h_b = 1.0$ and 2.0 m at $U_{10} = 10$ m/s. No physical reason can be found for this behavior; it can only be surmised that this represents a model inconsistency. However, this problem does not detract from the general result that at such shallow bay depths the barrier protects the mainland only if the bay is narrow.

While the above results document the range of wind speed and bay depths for which barrier islands may reduce the wave height at the mainland shoreline, they do not give any information on the actual wave heights predicted by the model. Figure 5 shows the wave height to depth ratio, γ_s, as a function of U_{10} for the range of water depths considered in Fig. 4. The wave height used is the stable wave height attained landward of the critical bay width (e.g. Fig. 1, distance = 25 km). Interestingly, γ_s is a complex function of both U_{10} and h_b, with a larger γ_s for a larger U_{10} but for a smaller h_b. In general, however, these bay γ_s values are smaller than the γ_s values for nearshore wave heights landward of the initial breakpoint (within the "saturated" surf zone), as observed from field data

(Thornton and Guza, 1982; Sallenger and Holman, 1985) and predicted by HISWA model runs conducted here. Apparently, HISWA predicts these lower bay γ_s values because of the cumulative dissipative effects of breaking and bottom friction over the constant bay water depths used.

The information presented in Fig. 5 potentially serves two purposes. First, wave height information may be used to constrain the results in Fig. 4; for example, a certain combination of U_{10}, h_b, and W_b may plot in the "protected by barrier" region, but have insignificant wave heights from an engineering standpoint. Secondly, the data in Fig. 5 can be compared with field data as a test of HISWA's performance in shallow water, although this was not accomplished here.

DISCUSSION

Modifying Factors

As described above, the results presented here strictly apply only to a highly idealized situation. Also, the results must be viewed as preliminary without a rigorous field verification of HISWA's predictions of shallow water wave generation and dissipation. Nevertheless, it is worth considering the effects of a number of complicating factors which will influence the application to a particular geographic location. These factors are summarized in Table 1.

One of the most important complicating factors relates to the use of a simplified topography, for which three entries appear in Table 1. Barrier island erosion is often accompanied by an overall retreat of the shoreface before the barrier itself is breached. In this case the bay width decreases (assuming the mainland shoreline does not also migrate landward) and the mainland shoreline is more likely to fall within W_{crit} (Table 1, A). However, if a shallow shoal remains after barrier island erosion, the difference between the barrier and no-barrier cases is reduced, thereby decreasing W_{crit} (Table 1, H). Similarly, if shallow bay shoals exist within W_{crit}, the removal of a barrier island will have less effect on wave heights reaching the mainland shoreline (Table 1, I).

Assumptions about wave and wind conditions may also have a significant influence on the overall assessment of a barrier island's wave mitigation role. The results presented here are for locally-generated wind waves; in windless swell conditions $H_s = 0$ in a barrier-protected bay. In this case the barrier is highly protective (Table 1, B) unless the bay is so wide and shallow that friction and breaking would effectively eliminate incoming swell without the barrier. A complete assessment of this complicating factor requires an understanding of the local wave climatology, including the partitioning of wave energy between locally-generated wind waves and non-local swell.

A non-normal angle of wind and wave incidence will reduce the effective W_{crit} by increasing the wave travel distance over the shallow bay depths (Table 1, G). However, this effect will be reduced by refraction of waves to a more onshore direction. Wind traveling over a barrier island will be diminished to a varying degree by the island's surface roughness;

W_{crit} will be increased because of the greater fetch required for waves to reach the stable bay height (Table 1, C).

Our methods implicitly assumed that the mean water level remains constant without regard for the significant storm surge and wave-induced setup that would naturally accompany the larger wind events. A surge can be viewed as increasing the bay depth (assuming the surge has entered the bay by other means, e.g. an inlet), thereby increasing W_{crit} (Table 1, D). Alternatively, the surge and wave-induced setup may be largely confined to the seaward side of the barrier (when inlets are small or distant), in which case the barrier configuration will clearly afford protection over the no-barrier configuration due to a larger h_b (and therefore larger stable bay wave height) in the no-barrier case. Both of the above effects will be reduced once the surge overtops the barrier and waves (along with the surge) start leaking into the bay from offshore.

Finally, a number of free parameters will influence W_{crit}. A trivial case is the determination of W_{crit} through the 10% matching criterion between barrier and no-barrier wave heights in the bay (Fig. 1). Obviously, a criterion of >10% will reduce W_{crit} while a criterion of <10% will increase W_{crit}. Less trivially, W_{crit} varies with HISWA's shallow water breaking coefficient or wave height to depth ratio (Table 1, F, K), and inversely with HISWA's bottom friction coefficient (Table 1, E, J). However, tests show that major variations in both these parameters have only a minor affect on W_{crit}. Therefore, the default values given by Holthuijsen et al. (1989) have been calibrated against field data and are probably adequate for the current work.

Site-specific Application

A rigorous application of the results presented here to a specific geographic location would require an evaluation of all the complicating factors described above. Nevertheless, a first approximation of the potential for a barrier island to protect the mainland shoreline from wave attack may be obtained by simply plotting the bay width over a W_{crit} curve for the appropriate water depth (assuming a reasonably simple barrier/bay profile). Figure 6 gives examples for two barrier/bay systems, both with an average bay water depth of $\sim$ 3.5 m, but with widely differing bay widths. From the figure it is evident that the barriers associated with north Chandeleur Sound (Louisiana, U.S.A.) have little potential to protect the mainland shoreline, while the barrier associated with Chatham Harbor (Cape Cod, Massachusetts, U.S.A.) has a large potential. Interestingly, the Chatham Harbor case is a well-documented example of a mainland shoreline that began experiencing acute erosion problems subsequent to the opening of a 1.3 km wide inlet through the barrier island (Giese, 1988).

Other Values of Barrier Islands

The results presented here provide only one component of a comprehensive assessment of barrier island's value as a protection against the open marine environment. Here we have focused only on wave height changes at the mainland shoreline, which we have implicitly assumed to be a proxy for changes in shoreline erosion rates. It is clear, however, that significant changes in wave height within W_{crit} may also impact the physical and environmental conditions of the bay floor, regardless of any changes in wave height at the mainland shoreline.

Other potential values of barrier islands include their role in mitigating storm surge and estuarine salinity intrusion. It is recommended that these factors be examined similarly to the wave height mitigation effect examined here.

CONCLUSIONS

The degree to which barrier islands mitigate locally-generated wave attack on the mainland shoreline is a first-order function of the wind speed, the bay depth, and the bay width. For any combination of bay width and depth, the barrier is predicted to control the wave height at lower wind speeds (up to the value of U_{10} at W_{crit}), while at higher wind speeds there is no such mitigating effect. Although the results are dependent on a number of complicating factors which are only qualitatively examined here, an overall conclusion can be made that wide, shallow bays have a strong controlling influence on the wave energy reaching the mainland shoreline, and in such cases the removal of the barrier island will make little difference. Conversely, barriers fronting narrow, deep bays appear to be essential for protecting the mainland shoreline from wave attack.

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Factors Increasing Protection by Barrier Islands
A. Migration of shoreline landward such that the bay width is decreased
B. Incoming swell not associated with local winds
C. Blocking of onshore wind by barrier island
D. Storm surge up to the point that barrier island is overtopped
E. Decreased bottom friction coefficient
F. Increased breaking coefficient (larger height/depth ratio)
Factors Decreasing Protection by Barrier Islands
G. Wind and waves at an angle to the coast other than directly onshore
H. A scenario in which a shoal remains after barrier island erosion
I. Shallow bay shoals within the critical bay width
J. Increased bottom friction coefficient
K. Decreased breaking coefficient (smaller height/depth ratio)

Table 1. Summary of additional factors and conditions influencing the importance of barrier islands for mitigating wave attack on the mainland shoreline.

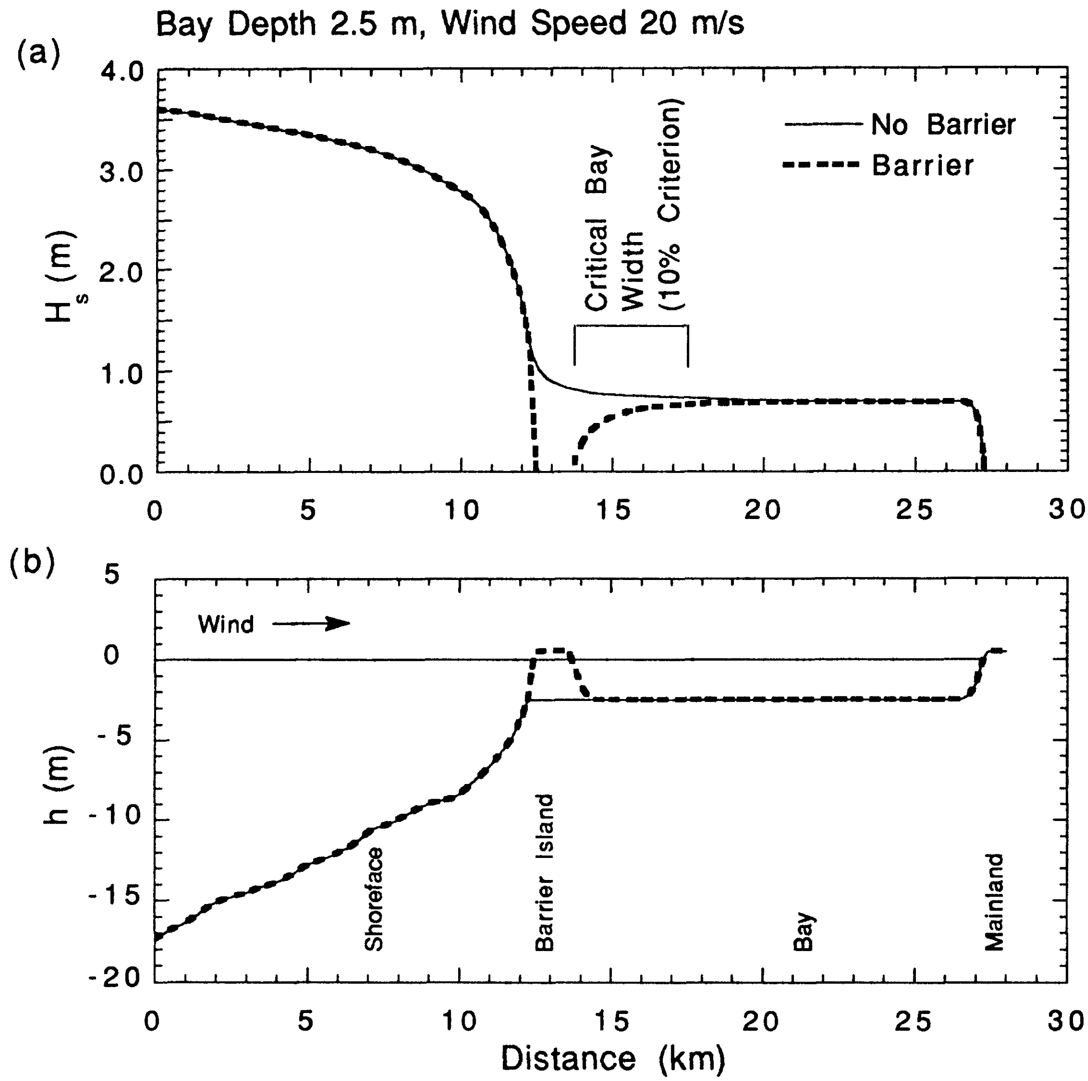

Figure 1. (a) Representative HISWA model run with the wave height, H_s, predicted for the barrier and no-barrier cases. The critical bay width, W_{crit}, is found as the bay width for which the no-barrier case H_s is increased over the barrier case H_s by 10%. (b) Definition diagram for idealized barrier/bay configuration used for HISWA model runs with h representing the water depth.

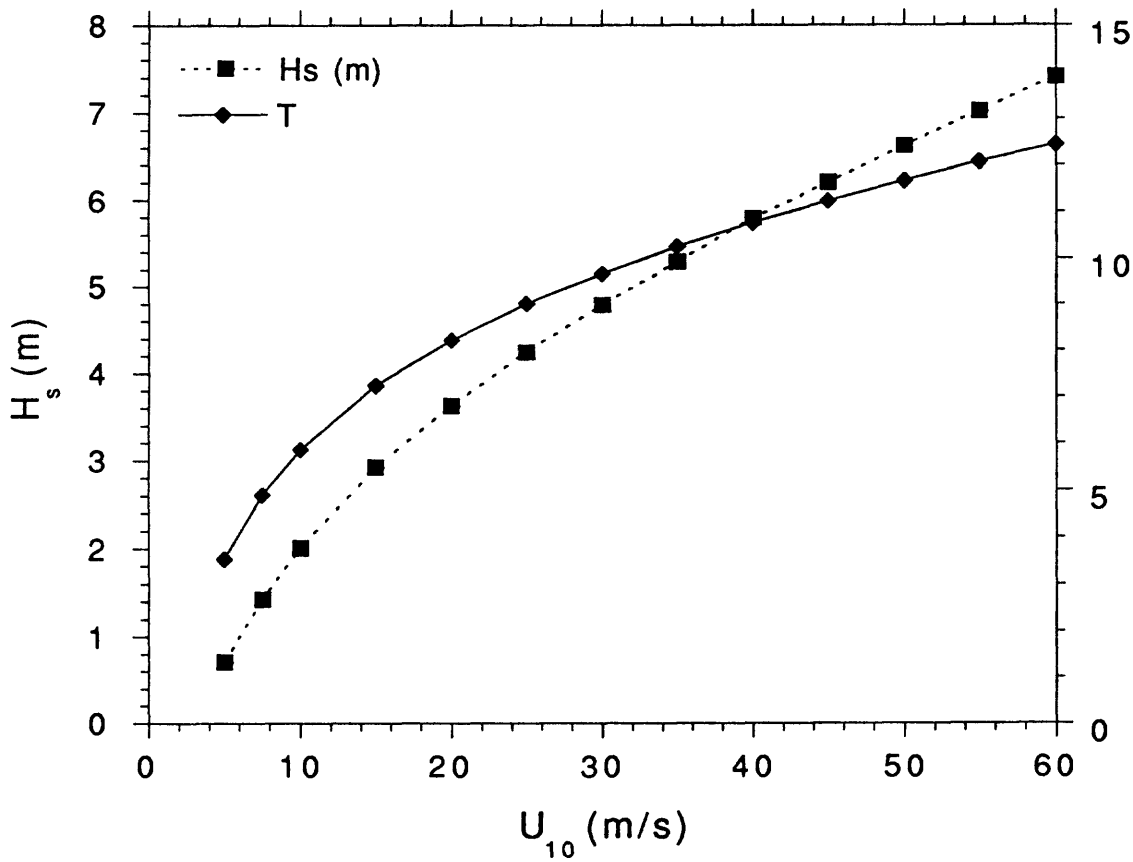

Figure 2. Significant wave height, H_s, and period, T, as a function of wind speed at 10 m elevation, U_{10}, used as the input boundary condition for HISWA runs. The assumed fetch is 300 km and the water depth used is 17 m. From eqns. 3-39 and 3-40 of the Shore Protection Manual (U.S. Army Corps of Engineers, 1984).

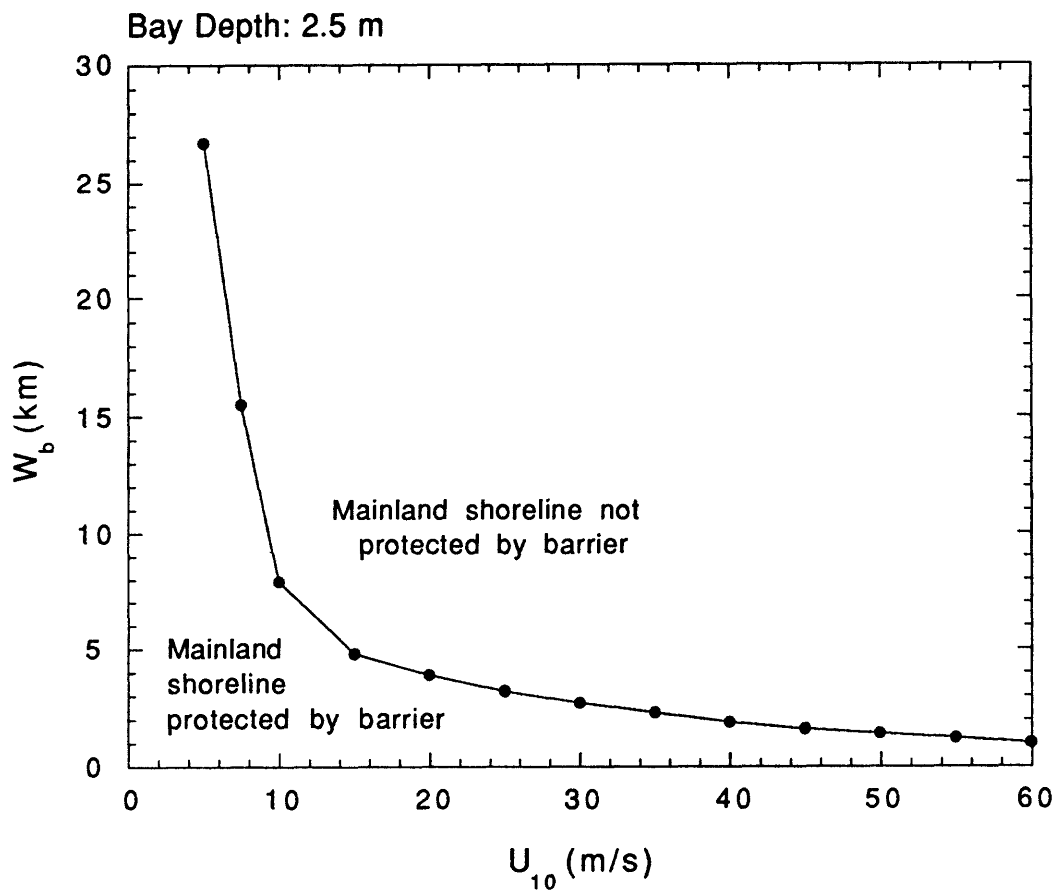

Figure 3. Model results for a bay depth of 2.5 m. The curve represents the critical bay width, W_{crit}, as a function of wind speed, U_{10}. The vertical axis is labeled as the bay width, W_b, and not as W_{crit}, to facilitate the use of this diagram for general bay widths (see text and Fig. 6).

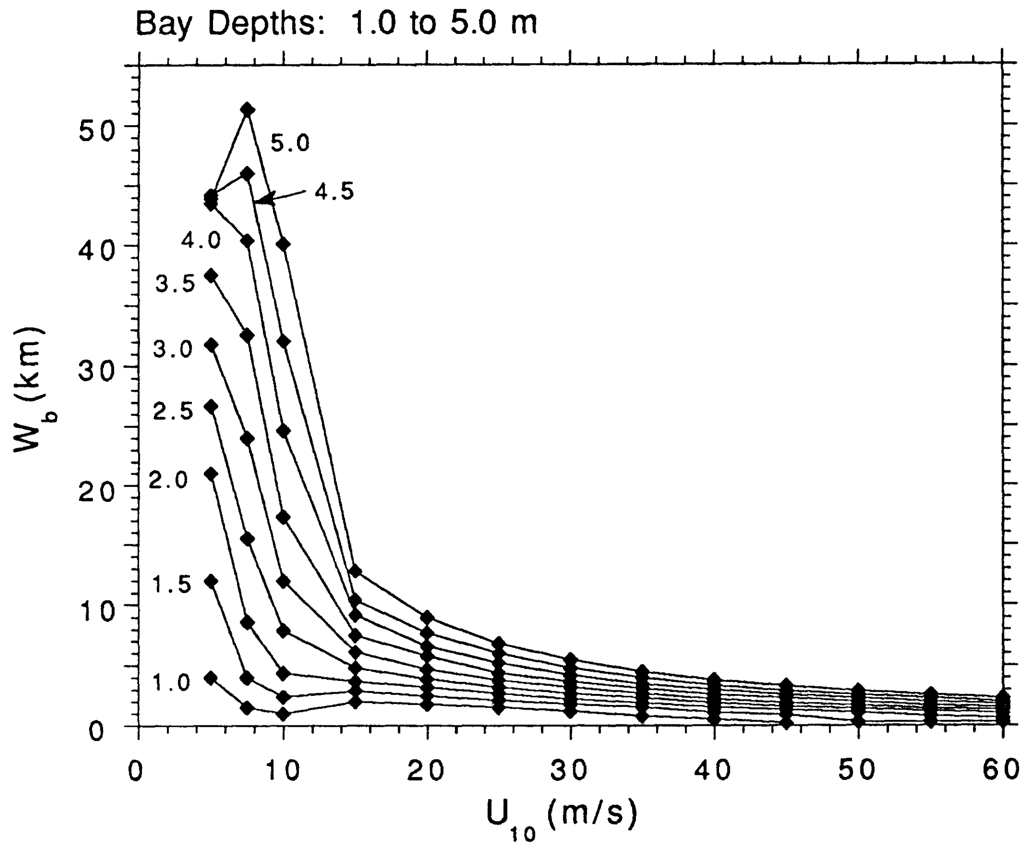

Figure 4. Same as Fig. 3, except showing critical bay widths for nine idealized bay depths from $h_b = 1.0$ to 5.0 m.

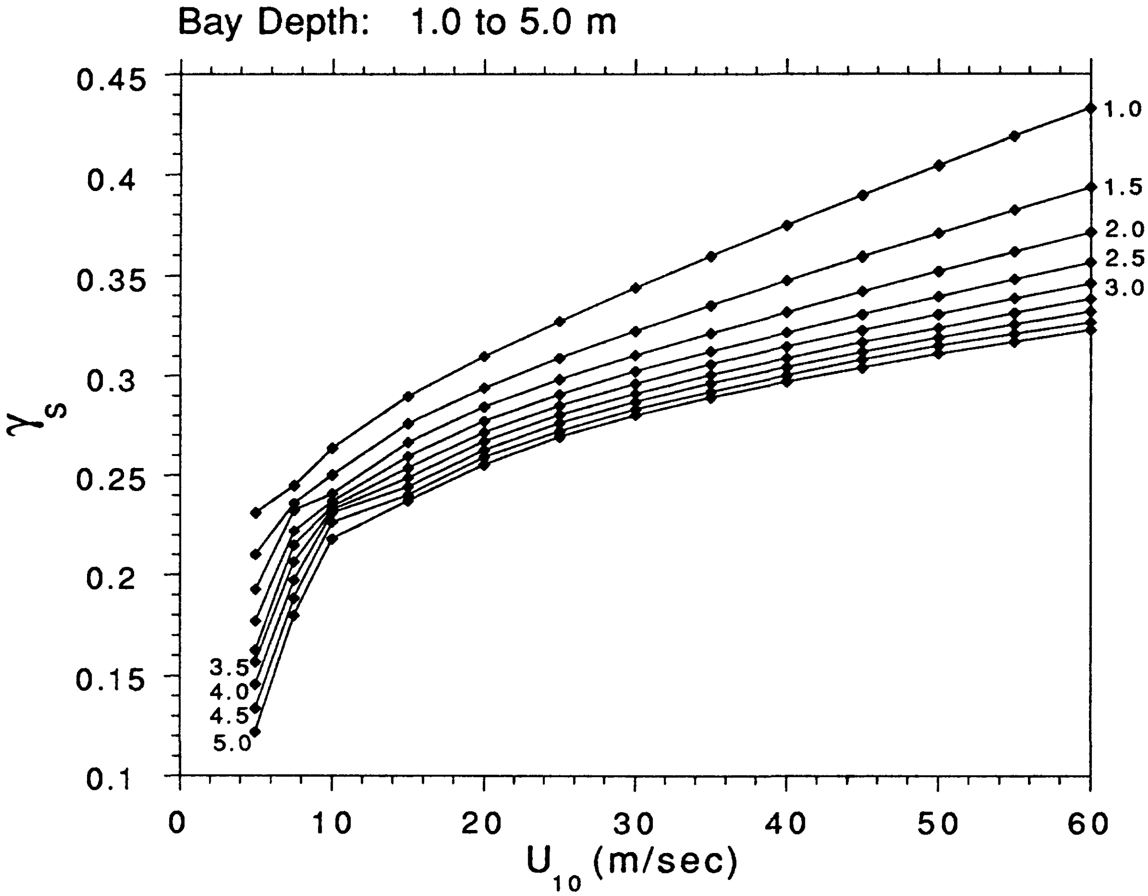

Figure 5. Ratio of significant wave height to bay depth, γ_s, as a function of wind speed, U_{10}, and bay depth, h_b.

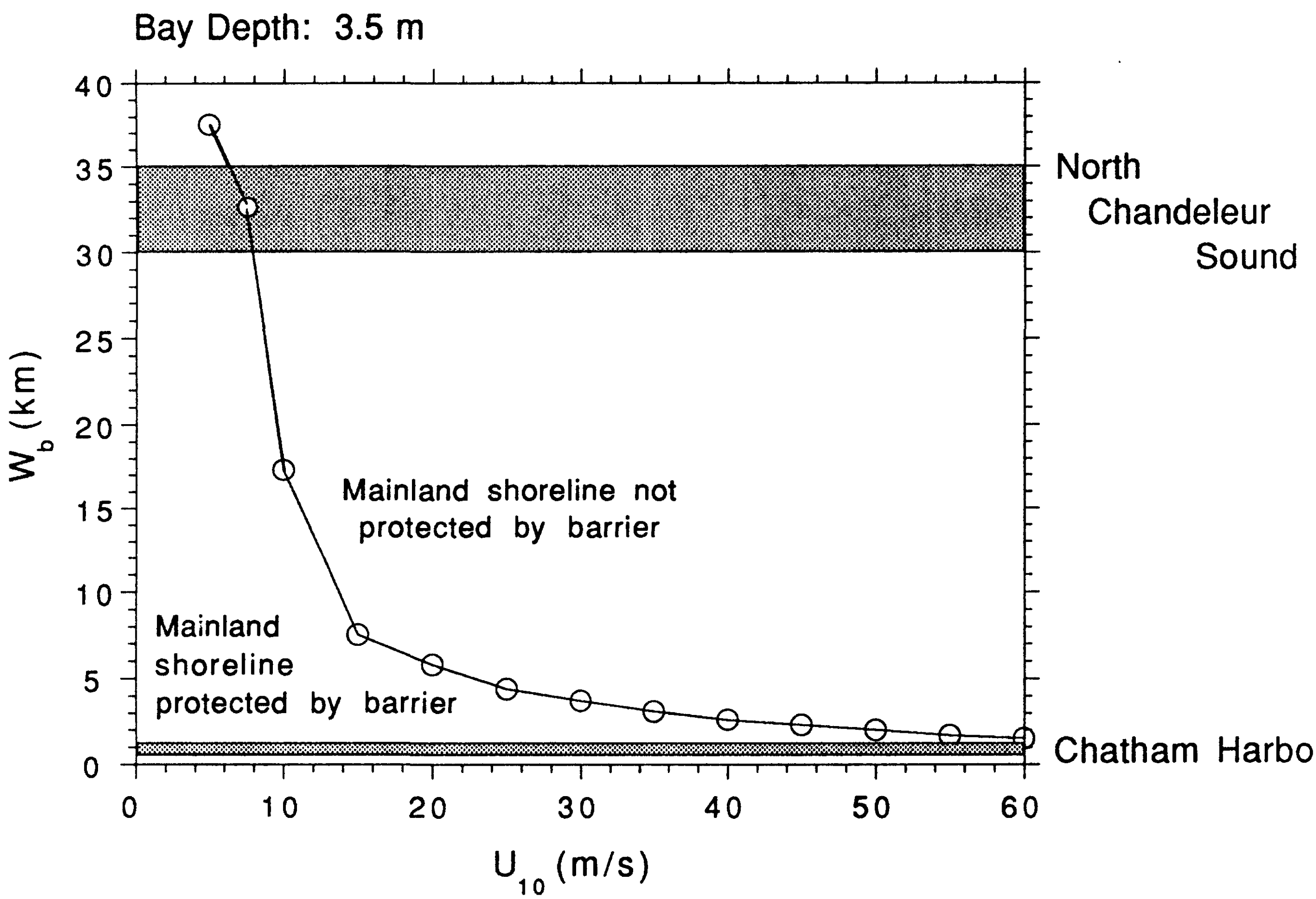

Figure 6. Generalized application of results to two U.S. barrier/bay systems with $h_b \approx 3.5$ m, but widely different bay widths. The shaded bands represent the approximate bay width ranges for the respective areas.