Preliminary Evaluation of Critical Wave Energy Thresholds at Natural and Created Coastal Wetlands

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PURPOSE: This technical note presents an evaluation of the wave climate at eight natural and created coastal wetland sites in an effort to identify the existence of critical wave energy thresholds for long-term marsh stability. This information could be used to help determine the minimum degree of protective structures necessary for successful establishment of created or restored coastal wetlands. Davis and Streever (1999) noted that some structures designed to protect dredged material wetlands may be overbuilt. If adequate protection could be provided by smaller, lower elevation structures, increased wetland functionality could be achieved at a considerable cost savings.

BACKGROUND: Coastal wetlands perform many functions, including shoreline stabilization, storm surge protection, water quality enhancement, and provision of habitats for fish, invertebrate species, waterfowl, and other wildlife (Stout 1990). Because of historic losses of coastal wetlands due to the combined effects of sea level rise and subsidence, as well as development pressures, the restoration and creation of coastal wetlands has become a priority in many regions (Figure 1). As early as 1968, the importance of vegetation in shoreline stabilization was recognized (Soil Conservation Service 1968), and many of the earliest salt marsh plantings were done specifically for this purpose. Although there has been considerable debate over the meaning of the word "success" in the context of wetland restoration, it is clear that in at least some cases "success" has been defined as a lack of shoreline erosion (e.g., Knutson, Ford, and Inskeep 1981).

Figure 1. Riprap breakwater used to reduce wave energy reaching a created salt marsh

Knutson, Ford, and Inskeep (1981) recognized the importance of wave stress and stated that it is "commonly the principal factor affecting initial establishment and long-term stability of salt marshes." Based on their observations of shoreline erosion at a number of planted marshes, Knutson et al. (1981) developed a subjective index of the probability of "success" that incorporated estimates of wind fetch distance, sediment grain size, and shoreline geometry. The relative exposure index (REI) developed by Keddy (1982) provides an estimate of wave climate that includes measurements of fetch distance, wind speed, wind direction, and percentage of wind occurrence. However, the potential effect of water depth on wave climate is not explicitly accounted for in this approach. Since for a given fetch and wind speed, the wave height can decrease as a wave propagates from deep to shallow water (*Shore Protection Manual* 1984), the inability to account for the effect of water depth on wave climate is a shortcoming of this approach. The REI has been used in a number of biological research applications to explore relationships between wave energy regime and sediment type, vegetation community composition, epibenthic faunal communities, and seagrass bed structure (e.g., Keddy 1982; Pihl 1986; Fonseca and Bell 1998). Although these indices may be useful for qualitative comparisons of wave energy among sites, neither of these indices provides sufficient information to serve as the basis for engineering structural designs for modification of the wave climate.

Since wave energy is a function of wave height squared (Pond and Pickard 1983), wave height is a good indicator of the amount of energy reaching the shore. Variables such as fetch distance, wind speed, wind direction, percentage of wind occurrence, and average water depth all interact to determine the wave climate at a given site. Since coastal marshes typically do not occur along shorelines exposed to high wave energy, it seems reasonable to hypothesize that there may be some threshold of wave energy above which natural marshes do not occur in the landscape. Using a modified version of Keddy's (1982) REI, Shafer and Streever (2000) found some evidence to suggest a maximum wave energy threshold for the existence of natural marshes in Galveston Bay, Texas. Identification of this upper threshold could serve as the basis for the development of guidelines for the placement of created marshes and the types of protective structures that may be required.

OBJECTIVES: The primary objective of this study was to evaluate a shallow-water wave hindcasting method for determining wave energy at natural and constructed wetland sites in an effort to identify critical thresholds for wetland establishment. The critical wave heights found in this study hope to address Davis and Streever's (1999) question "How low can you go?" regarding the height of protective structures at created or restored coastal wetlands. A secondary objective was to compare the estimates of wave energy obtained from wave hindcasting with the more computationally simple REI calculated by Shafer and Streever (2000).

SITE DESCRIPTIONS: Five sites along the coast of Texas and three sites along the Alabama coast were selected for analysis (Table 1). Sites were chosen to represent varying levels of wave energy ranging from high-energy sites lacking natural estuarine wetlands (Pelican Point and Bolivar Peninsula), to lower energy sites with extensive natural wetlands and stable shoreline configurations (Point aux Pines West and Point aux Pines East). In addition, three created wetlands subject to moderate wave energy with varying levels of structural protection were compared (Mitchell Energy and Aransas National Wildlife Refuges sites127A (Figure 2a) and 128 (Figure 2b)).

a. Site 127A

b. Site 128

Figure 2. Aransas National Wildlife Refuge sites 127A and 128. The crest elevation of the riprap breakwater at site 127A is +3.5 ft mean low tide (MLT), while the crest elevation of the geotextile tube at site 128 is lower, ranging from +2.0 to +2.4 ft MLT

The Bolivar Peninsula (BP) site, in Galveston Bay, Texas, was originally created in 1976 using dredged material substrate. For the first few years, temporary wave protection in the form of sandbag dikes and floating tire fences was provided. After several seasons, these structures deteriorated, and a portion of the original planted marsh has since been lost due to erosion. The Elmgrove Point (EP) site is a large natural *Spartina alterniflora* marsh located along the Bolivar Peninsula a few miles east of the BP site that has some evidence of shoreline erosion, although no specific information regarding shoreline change was available. The remaining three sites in Texas are constructed dredged material wetlands located near Aransas Bay. The wave climate at the Texas sites had been previously compared by Shafer and Streever (2000) using a modified version of Keddy's (1982) REI. The shoreline of the Pelican Point site, located in Mobile Bay, Alabama, is characterized by coarse sandy sediments and an absence of emergent marsh vegetation. The remaining two sites, Point aux Pines east and west, are natural coastal wetlands located along the mainland Alabama coast of Mississippi Sound.

Table 1
Site Locations

Site	Symbol	Location	Latitude	Longitude	Structures
Pelican Point	PP	Mobile Bay, AL	30°23.55	87°50.60	No
Point aux Pines (east)	PAPE	Mississippi Sound, AL	30°22.50	88°18.20	No
Point aux Pines (west)	PAPW	Mississippi Sound, AL	30°22.50	88°18.70	No
Bolivar Peninsula*	BP	Galveston Bay, TX	29°25.44	94°44.21	Temporary
Elmgrove Point	EP	Galveston Bay, TX	29°27.89	94°41.26	No
ANWR 127A*	127A	Aransas Bay, TX	28°13.59	96°47.34	Yes
ANWR 128*	128	Aransas Bay, TX	28°12.65	96°48.84	Yes
Mitchell Energy*	ME	Aransas Bay, TX	28°09.88	96°52.39	Yes
*Created Marsh					

METHODS:

Wave Hindcasts: WaveGen (Weggel and Douglass 1985), a computer program based on shallow-water wave generation models recommended in the *Shore Protection Manual* (1984), was used to hindcast the nearshore wave climate (direction, height, frequency of occurrence). The following modified shallow-water equations are based on Hasselmann's (1976) deep water equations:

$$gH/U^* = 0.283\tanh\left(0.530\left(gd/U^*\right)^{3/4}\right)\tanh\left(0.00565\left(gF/U^*\right)^{1/2}\right)\tanh\left(0.530\left(gd/U^*\right)^{3/4}\right) \quad (1)$$

$$U^* = \left(0.17U^{1.23}\right)^2 \quad (2)$$

where
- g = acceleration due to gravity
- H = wave height
- F = fetch
- d = average water depth
- U = wind speed
- U^* = adjusted wind speed

The computer code WaveGen solves this equation iteratively with two other equations in the *Shore Protection Manual* for the time needed to obtain fully arisen conditions and for wind speed at different averaging intervals.

For the Alabama sites, summary wind data (direction, speed, and frequency) from 1964-1991 were obtained for Mobile Airport (EarthInfo, Inc.) in 10-degree sectors. For the Texas sites, summary statistics were based on 1997 wind data gathered by the Conrad Blucher Institutes (Corpus Christi, Texas) provided in 16-degree sectors (Shafer and Streever 2000). Fetches were measured for each of the corresponding wind sectors. Water depths across the entire fetch lengths were obtained from National Oceanic and Atmospheric Administration (NOAA) charts (using mean low water (MLW)). An average water depth along the entire fetch was calculated for use in the wave generation equations. Detailed nearshore, wave refraction, and diffraction modeling were not a specific part of this hindcast.

Wave heights were hindcast using the WaveGen shallow-water wave models and entered into a spreadsheet. The percent of time each wave height occurred was found by the percentage of time a given wind speed occurred from each wind direction. Wave heights were summed for all wind directions to find the total number of occurrences for each wave height and the percentage of time each height was exceeded. The hindcast wave statistics were originally intended to be modified to account for the reduction in wave height due to nearshore breaking using the concepts of shallow-water energy saturation (Thornton and Guza 1982); however, according to the NOAA bathymetry charts, the sites chosen did not have shallow sand or mud bars reducing water depths away from shore. Water depth limitations will still transform wave heights entering the shore, but anomalous features (like sand or mud bars) that could severely alter wave models were not observed among the sites.

At the three sites where structures designed to reduce or eliminate wave heights were present, wave transmission coefficients were calculated in order to estimate the amount of wave energy impacting the wetland shoreline. The coefficients were chosen using methods outlined in the Shore Protection Manual (USACE 1984) and Soresen (1997). Water levels were assumed to be at mean water level (MWL) for this modification.

Two wave height statistics were calculated for each site. In order to compare the amount of wave energy capable of reaching a shoreline prior to structural influence, *incident* wave heights were calculated. *Incident* wave height is defined here as the wave height capable of reaching the shore during low tide *prior* to structural influence (Figure 3). The second statistic is the *wetland* wave height, which is defined here as the wave height capable of reaching the wetland after structural influence (Figure 3). At the five sites where no structures are present the wetland and incident wave height statistics are equal.

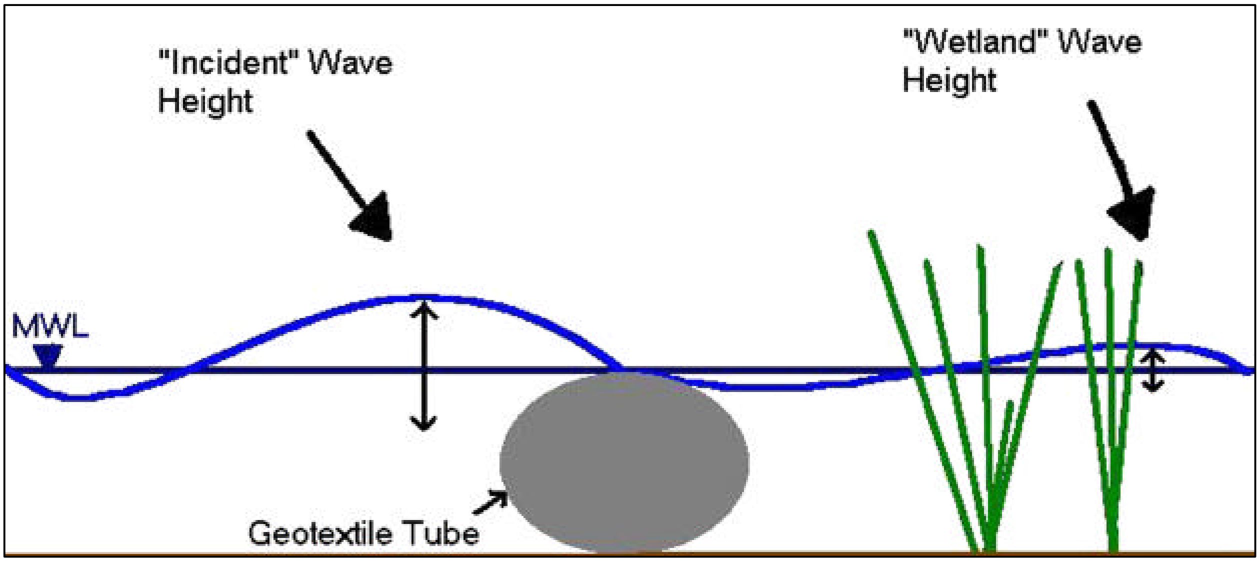

Figure 3. Comparison of incident wave height and wetland wave height

This wave hindcasting procedure allows for a complete time-series of estimated wave heights for the period of the wind record. For analysis here, however, those time-series were evaluated for their percentage exceedance statistics. These are an estimate of the percentage of time any nominal wave height level has occurred or been exceeded. Since they were based on the MLW depths, they could be considered slightly conservative.

Relative Exposure Index. The following equation was used to calculate the REI for each of the Texas sites (Shafer and Streever 2000):

$$REI = \sum_{i=1}^{16} V_i \times P_i \times F_i / 100 \tag{3}$$

where

V_i = mean annual wind speed, km/hr, from each of the 16 cardinal and subcardinal compass bearings

P_i = percent frequency that the wind blew from 16 cardinal and subcardinal compass bearings

F_i = fetch distance, km, in each of the 16 cardinal and subcardinal compass bearings

REI values are reported here only for the Texas sites.

RESULTS AND DISCUSSION:

Wave Hindcast Statistics. Percent exceedence of wave height (percent of time wave heights are above any one value) varied between sites (Figures 4 and 5). Since this is the first study examining this sort of wave climate statistics in relation to wetland establishment, it was not clear which wave height statistic would be the best indicator of the critical wave height for vegetation establishment and shoreline stabilization. The 50th and 20th percentile exceedence wetland wave heights were selected here for discussion and comparison with observed shoreline stabilization and vegetation characteristics. The 50th percentile wave height represents “average” conditions, which would be exceeded 50 percent of the time. The 20th percentile represents more extreme conditions, which would be exceeded only 20 percent of the time. It is possible that the more extreme wave conditions represented by the 20th percentile statistics heights have a greater influence on long-term shoreline stability than the more typical conditions represented by the 50th percentile statistics.

At the 20th and 50th percentile exceedence wave heights, the rank orders of the sites (from highest to lowest) in terms of wave energy were similar. The BP site was ranked highest, and the two natural marshes in Mississippi Sound (PAPE and PAPW) were ranked lowest (Table 2). The rank order of the remainder of the sites varied depending on whether the 20th percentile or the 50th percentile statistics were used. If high wave energy is a limiting factor for vegetation establishment, then the rank order of sites should be consistent with visual observations regarding the presence or absence of vegetated wetlands and shoreline erosion. The patterns observed in this study suggest that the 20th percentile wave height statistics may be better indicators of long-term shoreline stability and vegetation characteristics than the 50th percentile statistics. The two sites that lack natural wetlands (BP and PP) have the highest values for the 20th percentile exceedence wave height; these results suggest that the values calculated for the 20th percent exceedence wave height at these sites (1.15 and 1.10 ft (0.22 and 0.33 m), respectively) (Figure 4) may represent the high side of a critical threshold for marsh establishment and long-term survival.

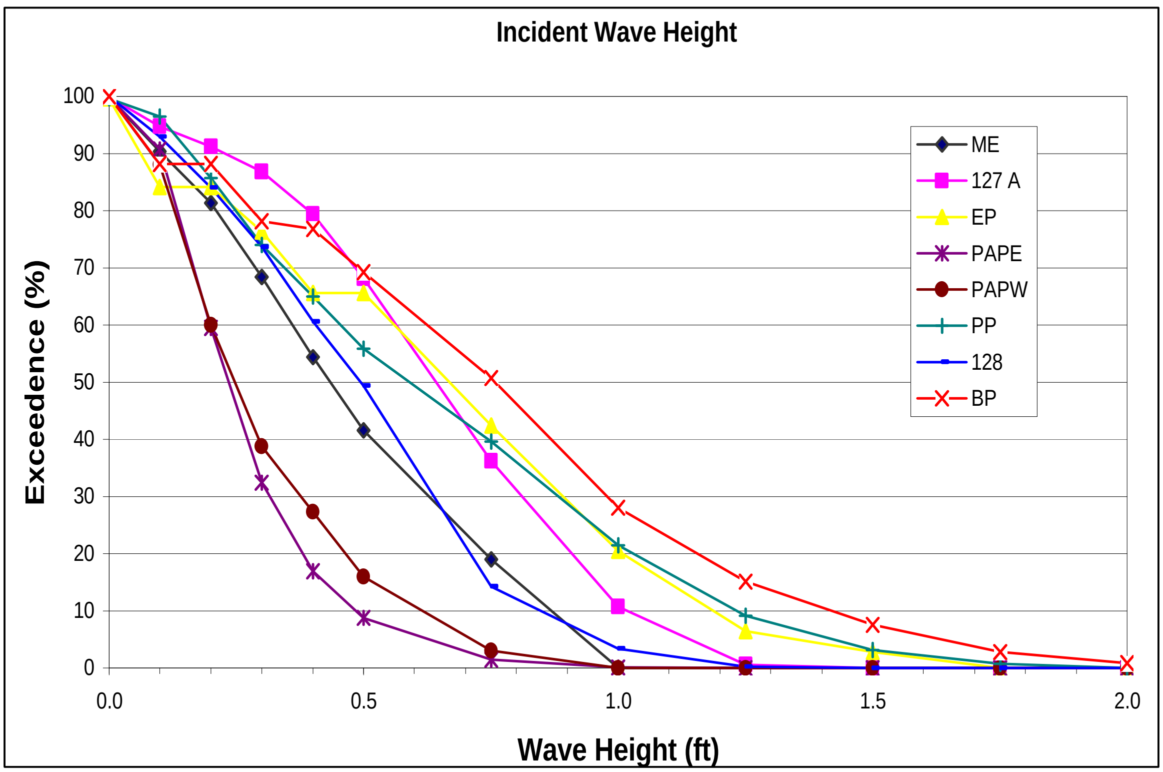

Figure 4. Exceedence curves for incident wave height (to convert wave heights to meters, multiply by 0.3048)

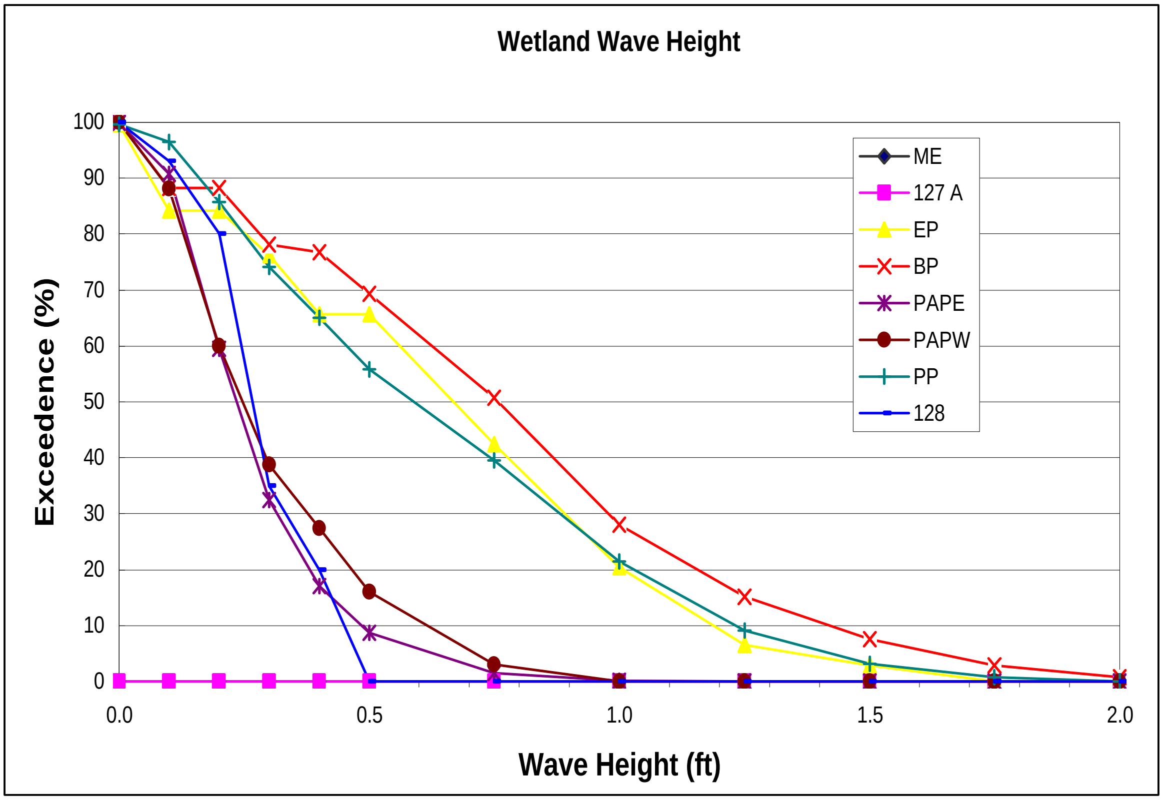

Figure 5. Exceedence curves for wetland wave height (to convert wave heights to meters, multiply by 0.3048)

Table 2
Comparison of Wave Climate Estimates Among Methods (sites presented in rank order from highest to lowest wave energy)

Site	Incident-20th, ft	Site	Incident-50th, ft	Site	REI
BP	1.15	BP	0.76	BP	95
PP	1.10	EP	0.67	ME	82
EP	1.00	127A	0.64	127A	77
127A	0.91	PP	0.59	EP	76
ME	0.73	128	0.49	128	59
128	0.71	ME	0.42		
PAPW	0.46	PAPW	0.25		
PAPE	0.39	PAPE	0.23		

Note: To convert wave heights to meters, multiply by 0.3048.

The third highest incident wave height occurs at Elmgrove Point (1.00 ft), where the shoreline exhibits some signs of erosion as well as the deposition of coarse shell fragments and other debris during periods of high wave activity (Shafer and Streever 2000). The lowest values for 20th percentile exceedence wave heights were observed at the two natural marshes in Mississippi Sound (PAPE = 0.39 ft (0.12 m) and PAPW = 0.46 ft (0.14 m)). Twentieth percentile incident wave heights for the three created wetlands in Aransas Bay (ME, 127A, and 128) ranged from 0.91 ft (0.28 m) to 0.71 ft (0.22 m) (Figure 4).

The large gap between the three sites of lowest wetland wave height statistics (PAPE, PAPW, and 128) and the three sites with highest wetland wave heights (BP, EP, and PP) (Figure 5) makes it more difficult to make predictions regarding the critical wave height range for the establishment of stable wetland shorelines. These preliminary results indicate that stable marshes can be maintained when the 20^{th} percentile exceedence wave height is $\leq$ 0.46 ft (0.14 m). Sites with 20^{th} percentile exceedence wave heights greater than 1 ft (0.3 m) did not support extensive natural marsh vegetation. Therefore, the critical threshold range is likely to be between 0.5 and 1.0 ft (0.15 and 0.3 m).

Implications for Structural Protection Design. Coastal wetlands, both natural and created, are apparently able to tolerate wave heights of up to 0.46 ft (0.14 m) at the 20^{th} percentile exceedence level. Created wetlands placed in this wave environment may require only minimal or temporary protection. The 20^{th} percentile exceedence incident wave height at all three constructed marshes with structures present ranged between 0.71 and 0.91 ft (0.22 and 0.28 m) (Table 2). These values are intermediate between those observed at stable natural marshes and the higher values observed at sites without natural marsh vegetation. Under these conditions, some form of structural protection seems warranted. However, coastal engineers should consider designing lower structures where the top elevations are nearer the wetland sediment surface. In tidal wetlands, wave protection structures are typically built with the top elevation of the structure well above the elevation of the wetland surface (Davis and Maynord 1998). This was the case for the structures at the ME and 127A sites, and given the conservative conditions of this model, wetland wave heights were reduced to zero at both sites (Figure 5). However, in riverine systems, there have been many successful projects where the top elevation of the structure is well below the design water surface elevation (Davis and Maynord 1998). In this study, the top of the geotextile tube at site 128 is near the marsh sediment surface, preventing bank undercutting and providing protection for the plant roots, while allowing the reduced wave energy to impact the flexible aboveground portions of the vegetation. The 20^{th} percentile exceedence wave height was reduced from 0.71 ft to 0.42 ft (0.22 to 0.13 m) at site 128 (Figures 4 and 5). Wave energy is further reduced as it passes through the vegetation due to the roughness provided by the stems (Knutson et al. 1982; Miller 1988). The apparent stability of this site suggests the design elevations of wave protection structures at some tidal wetlands could be reduced without presenting a serious risk of shoreline erosion.

Larger structures are not only more costly to build, but may reduce the overall functional capacity of the wetland by altering the characteristic hydrological regimes and restricting access to the marsh surface. Nutrient and biogeochemical cycles that depend on regular tidal inundation may be affected. In addition, the reduced sediment input may limit the ability of the wetland to keep pace with sea level rise and subsidence. The habitat value of the wetland for fish and invertebrate organisms may be reduced if these organisms are unable to utilize the marsh surface for feeding or refuge from predation. If created wetlands are to replace the functions of natural wetlands, then the hydrological cycles of created marshes should mimic the natural tidal cycles to the extent possible, without exposing them to undue risk of erosion.

Comparison of Wave Height Statistics with REI. The rank order of the sites, from highest to lowest in terms of wave energy, is similar for the hindcast wave statistics presented here and the REI approach. The BP site was consistently ranked highest and the 128 site was consistently among the lowest regardless of the statistic chosen as an indicator (Table 2). There were some minor differences. For example, the ME site had the second highest REI score, but ranked near the bottom according to the wave hindcasts (Table 2). The differences in the ranks of sites are most likely due to the effects of varying water depth on wave generation, which is not accounted for in the REI equation. Although the REI has been used in a number of biological research applications to explore relationships between wave energy regime and sediment type, vegetation community composition, epibenthic faunal communities, and seagrass bed structure (e.g., Keddy 1982; Pihl 1986; Fonseca and Bell 1998), this is the first study that compares REI scores with estimates of wave heights generated using wave hindcasting techniques. The similarity in wave energy ranks should be expected considering that the REI uses some of the parameters involved in wave generation. The similarity also demonstrates that the computationally more simple REI provides a valid approximation of the wave climate for use by scientists interested in identifying relationships between ecological characteristics and the physical environment.

However, there are at least two strong arguments for moving toward a wave height approach such as the one outlined in this technical note. First, wave height is a real variable. It is well accepted as the primary measure of wave energy in the oceanographic and engineering communities. It is also dimensionally meaningful and consistent. Second, as computed here, a wave height approach allows for all of the parameters that are known to control wave energy to be explicitly considered. This includes water depth and breaking induced by structures.

CONCLUSIONS: This study presents evidence to support the idea of a critical wave energy threshold for wetland establishment and shoreline stabilization. It also outlines a promising approach to estimating wave energy at wetland sites based on existing wave hindcasting techniques. The 20 percent exceedence wave height appears to be consistent with visual observations regarding the presence or absence of marsh vegetation and shoreline stability. At the 20th percentile level, the preliminary data reported here indicate a critical threshold wave height between 0.5 and 1.0 ft (0.15 and 0.3 m). Due to the limited number of sites in this study, additional sites with intermediate wave statistics should be examined. It is also possible that the threshold values will differ between regions due to differences in sediment type, vegetation composition, nutrient availability, or other environmental factors. Secondary implications of this study would suggest that the top elevation of some structures could be placed nearer the marsh sediment surface and still provide adequate protection. This would provide two benefits, both reduced project costs and increased wetland functional capacity.

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