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Idealized Marsh Simulations: Sensitivity of Hurricane Surge Elevation and Wave Height to Bottom Friction

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PURPOSE: The purpose of this CHETN is to examine changes in peak surge elevation and wave height due to changes in the frictional resistance of a marsh. Landscape features with vegetation have the potential to reduce storm surge elevations and dissipate wave energy. Land elevations greater than the storm surge elevation act as a physical barrier and create bathymetric resistance for the surge and waves. Landscape features such as marshes also have the potential to create frictional resistance and affect storm surge and wave energy even when below the surge elevation. This is the third in a series of technical notes on the influence of marshes on storm surge and waves. The analysis in this note isolates the sensitivity of the modeled storm surge elevation and wave height to the magnitude of bottom friction change and indicates, in a qualitative sense, the degree to which a marsh density may reduce storm surge elevation and wave height on the coast. The magnitude of bottom friction was systematically increased within a hypothetical marsh area to understand how marsh vegetation type and density may modify storm parameters (surge elevation and wave height) on the coast immediately landward of the marsh.

METHODOLOGY: A set of idealized surge simulations using ADCIRC (Westerink et al., 1992) and STWAVE (Smith et al., 2001) were made to examine changes in storm surge elevation and wave height with changes in various marsh characteristics, such as elevation, vegetation cover, shape, and continuity (degree of segmentation). This note presents results for changes in bottom friction, while accompanying technical notes evaluate other marsh characteristics. The modeling process involved an ADCIRC simulation followed by an STWAVE simulation, and finally a re-run of ADCIRC that includes wave radiation stress obtained from the STWAVE results. The modeling system applied is described by Bunya et al. (2009) and Wamsley et al. (2009). The model system was validated against high water marks for Hurricanes Katrina and Rita and results were generally within +/- 0.5 m of measurements. This study is a sensitivity analysis to assess how model results change for changes in coastal marsh-like features. Results presented in this note depict wave conditions and total surge levels driven by wind, atmospheric pressure, and wave radiation stress.

The idealized grid domain applied in this study included straight and parallel bathymetric contours on a 1:1000 continental shelf with a single perturbation (landscape feature representative of a marsh) positioned along the northern Gulf of Mexico, in the vicinity of southeastern Louisiana (Figure 1). The landscape feature is represented by a 400 km^2 portion of the coastline (the approximate size of Biloxi Marsh in southeastern Louisiana). Figure 2 depicts a cross section view of the idealized feature, representative of a marsh at high water. To estimate resistance imposed by vegetation within the water column, Manning's *n* is modified from the open water value of 0.020. While vegetative drag is dependent upon characteristics including vegetation density, height, and rigidity, the Manning's *n* value provides a qualitative estimation of the velocity reductions associated with vegetated flow. Manning's *n* values of 0.020, 0.035, and

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0.150 are approximately representative of an unvegetated sandy surface, an area covered with high grass, and a densely wooded area, respectively (Chow, 1959) and are representative of values for open water, saline marsh and woody wetland, validated against hindcasts of hurricanes Katrina and Rita (Bunya et al. 2009). The highest Manning's *n* used in this study, 0.300, represents an upper limit that has been suggested by some researchers for tall marsh grass (e.g. Hall 1994, Järvelä 2002). However, the authors view this value as an unrealistic upper limit. The marsh is backed by a non-overtopping wall representative of a levee.

Six hurricanes of varying size and intensity were simulated with each of the marsh configurations to examine the surge response to varying meteorological conditions. Table 1 lists the characteristics of the idealized storms applied in this study. Each storm track was selected such that the maximum winds impact the center of the marsh with a storm forward speed of 5.6 m/s (20.2 km/h). Landfall pressures range from 900 to 975 mb, while radii of pressure range from 20.4 to 74.1 km. The surge potential in Table 1 is the peak surge averaged over the marsh, and the wave potential is the peak wave height averaged over the marsh.

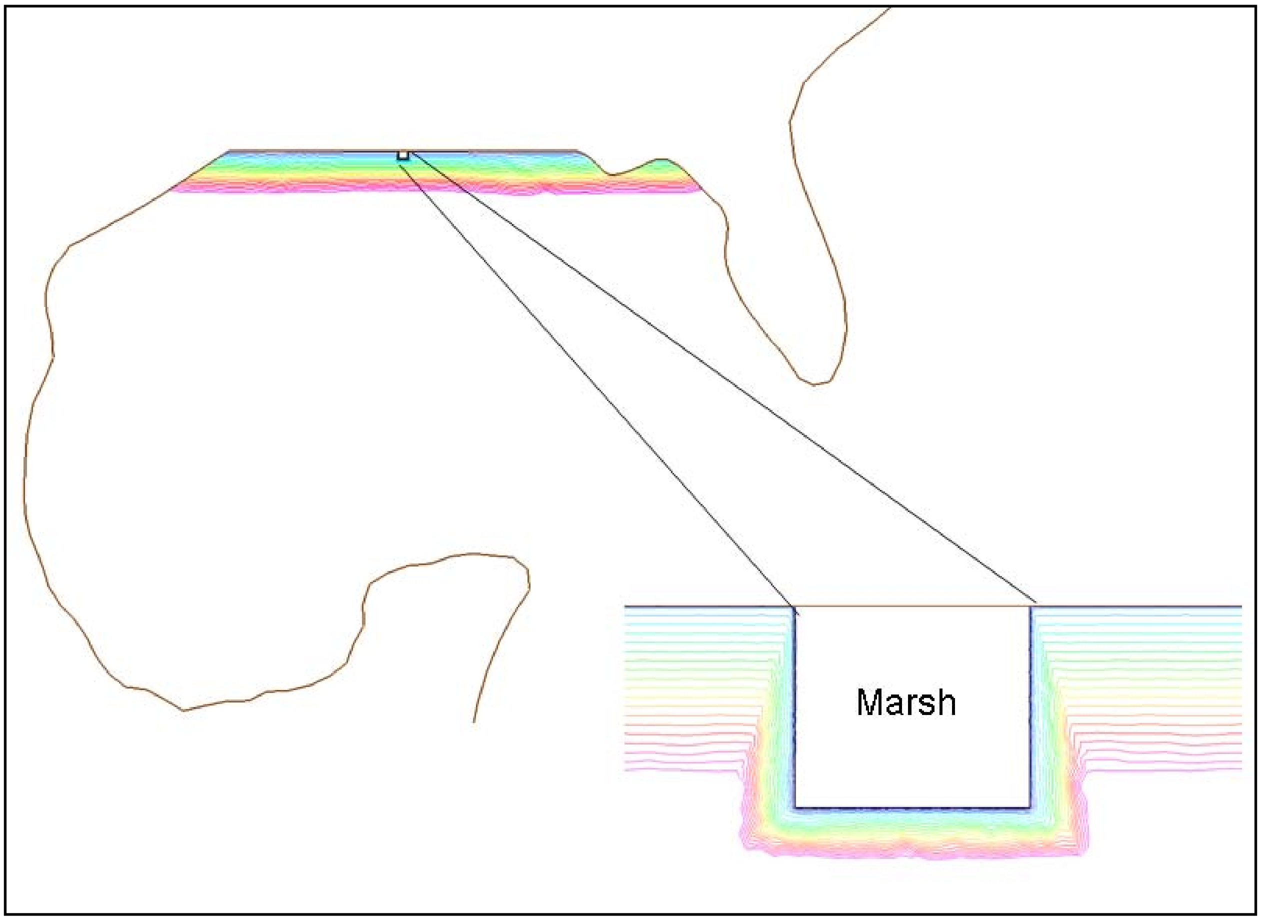

Figure 1. Idealized marsh-like coastal feature within ADCIRC domain.

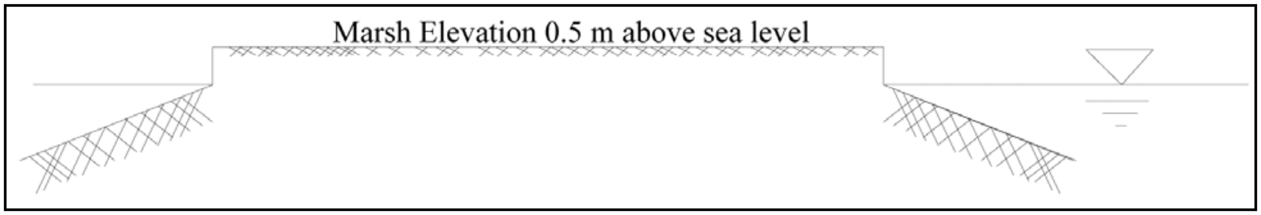

Figure 2. Sample cross section of idealized marsh-like feature.

Table 1. Storm Suite.

Landfall Pressure Radius (km)	Pressure at Landfall (mb)	Surge Potential, ζ_{base} (base configuration, m)	Wave Potential, H_{base} (base configuration, m)
20.4	975	1.8	0.2
38.9	975	2.2	0.6
38.9	941	3.5	1.4
20.4	900	4.4	2.0
38.9	900	5.2	2.6
74.1	900	6.0	3.0

RESULTS: Figures 3 and 4 provide a summary of storm surge and wave height sensitivity to bottom friction. Figure 3 depicts percent differences in peak surge and Figure 4 depicts differences in peak wave height from a base condition marsh having a bottom friction represented by Manning's *n* of 0.020 (sandy bottom). Peak surge changes outside the limits of the marsh (where bottom friction is held constant at 0.02 for all configurations) are less than +/- 10 percent as a result of enhanced bottom roughness within the marsh region. Due to the east-to-west surge propagation at hurricane landfall, increases in surge levels east of the marsh are a result of slowed surge propagation. Conversely, surge levels are lowered west of the marsh due to the shadowing of the marsh feature. As the center of the storm makes landfall, direction of flow transitions from westward to eastward, and the shadowing/buildup effects are reversed. The superposition of these effects causes changes in surge outside the marsh, ranging from negligible (less than +/-5 percent in storms of large pressure radius) to low (+/-5 to 10 percent in storms of small pressure radius). Changes in peak wave height outside the marsh are also negligible (less than 0.2 m).

Wave results in this study indicate waves breaking on the marsh, resulting in relatively low wave heights within the idealized marsh. A comparison of surge results both including and excluding wave radiation stress indicates a setup of the water levels along the seaward edge of the marsh. Seaward of the marsh, a set-down of water levels is observed prior to the breaking point. For the storm of highest potential, base case water levels are increased by 0.4 m due to wave set-up and decreased by 0.1 m due to wave set-down. A narrow band of wave setup is also evident adjacent to the coastal boundary of the grid, stemming from wave breaking along the non-overtopping levee representing the coastline.

As shown in Figure 3, surge is sharply decreased within the marsh feature as a result of increased bottom friction. An increase in Manning's *n* from 0.020 to 0.035 results in a decrease in peak surge of over 35 percent for the storm of lowest surge potential (ζ_{base} = 1.8 m). As bottom friction is increased to a Manning's *n* of 0.050, surge levels are reduced by over 50 percent for the storm of lowest surge potential. As expected, the upper bound of *n* = 0.300 results in the most extreme reductions in surge levels.

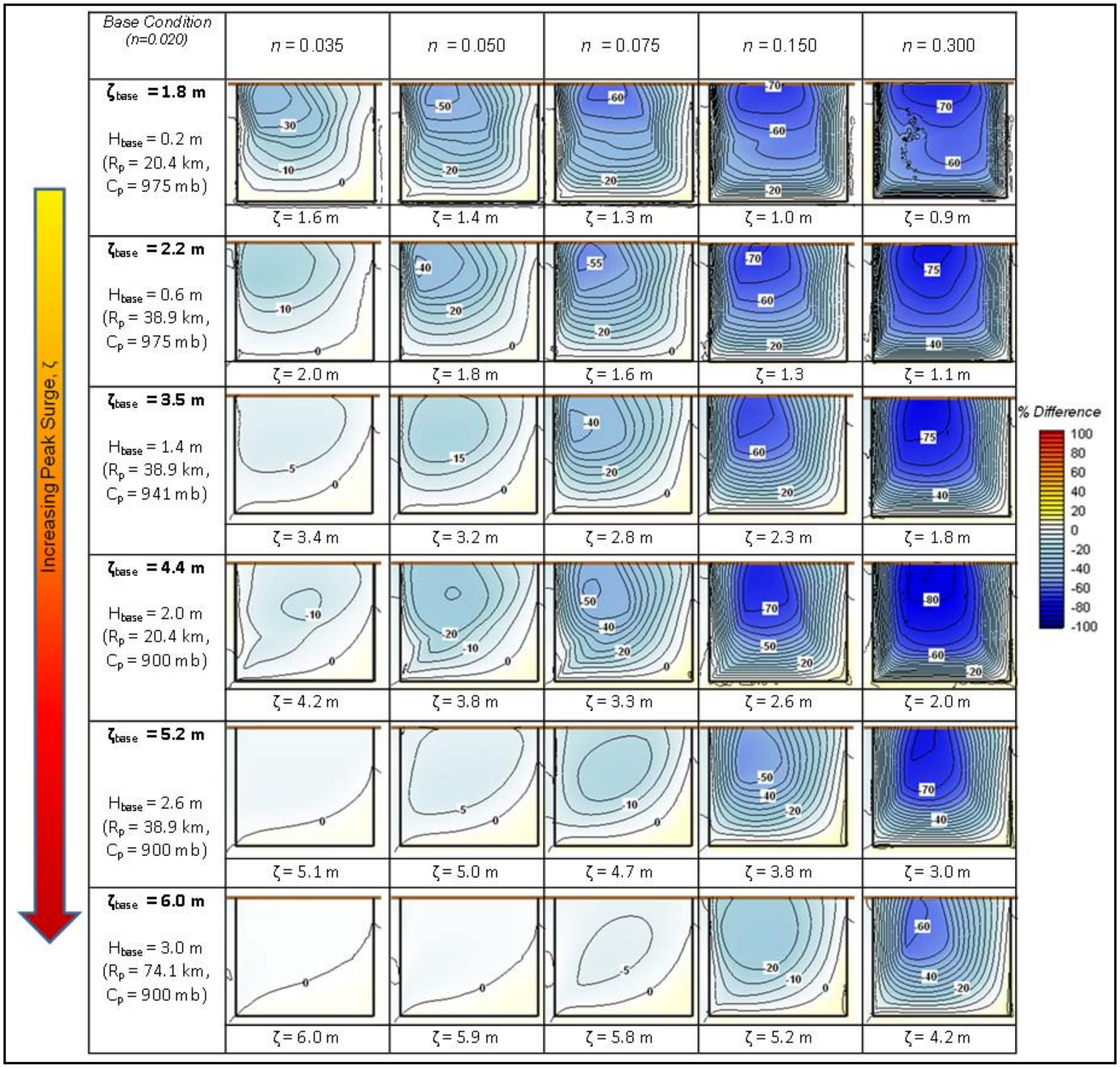

Figure 3. Percent change of peak surge response due to increased bottom friction compared to a marsh feature having bottom friction represented by a Manning's *n* of 0.020. Hot colors indicate surge increases, while cool colors indicate surge decreases, relative to the base condition. Top of square represents coastline. Average peak surge within each base case square is represented by ζ_{base}. Average peak surge within each experimental marsh square is denoted by ζ.

In general, the sensitivity of storm surge to increased bottom friction decreases with increasing surge potential, as was observed by Loder (2008) regarding sensitivity to seabed elevation. This is seen in Figure 3 as the plots become less blue as the surge potential increases (from top to bottom). For example, Manning's *n* = 0.035 results in a very slight reduction (less than

5 percent) in surge for a storm of high surge potential (ζ_{base} = 6.0 m). However, the storm producing a surge potential of ζ_{base} = 3.5 m results in a 15 percent decrease in surge levels due to an increase in bottom friction of Manning's *n* of 0.020 to 0.050, while a surge potential of ζ_{base} = 4.4 m results in a 25 percent decrease. This exception indicates that sensitivity to bottom friction is influenced by the peakedness of the alongshore surge distribution (Loder 2008). The storm producing a ζ_{base} of 4.4 m has a radius of pressure of 20.4 km, while the storm producing a ζ_{base} of 3.5 m has a radius of pressure of 38.9 km.

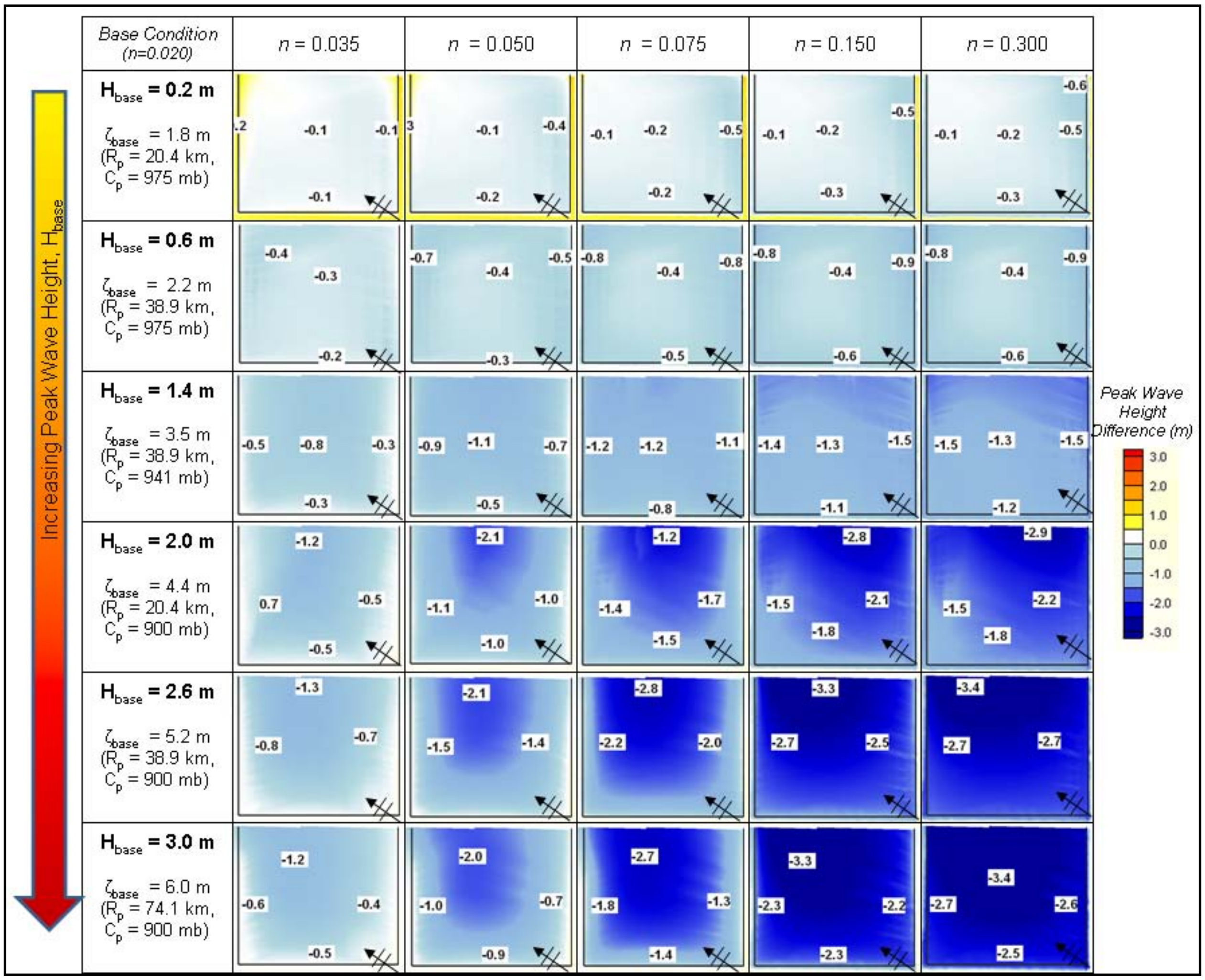

Figure 4. Changes in peak wave height due to increased bottom friction compared to a marsh feature having bottom friction represented by a Manning's *n* of 0.020. Hot colors indicate wave height increases, while cool colors indicate wave height decreases. Top of square represents coastline. Average peak wave height within the marsh square is represented by H_{baee}. Arrows indicate dominant direction of waves approaching the marsh.

Increased bottom friction reduces wave heights within the marsh for all configurations in this study. Decreases in wave height ranging between 0.1 to 0.8 m are observed as bottom friction is increased to *n* = 0.035 for the three storms of lowest wave potential (H_{base} = 0.2, 0.6, and 1.4 m). As wave potential increases, wave height reductions become more dramatic, as shown in the lower lines of Figure 4. For an increased bottom friction of Manning's *n* = 0.020 to 0.035, wave heights are reduced by at least 1.2 m for the three storms of greatest wave potential (H_{base} = 2.0, 2.6, and 3.0 m). The increased wave height reduction for the more intense storms is due to the fact that dissipation is related to wave height squared, so the dissipation increases nonlinearly with wave height. Wave period also increases with storm intensity which again increase wave dissipation. Figure 5 plots the relationship between the ratio of peak wave height to total water depth (H_{base}/h) and bottom friction. As bottom friction increases, H_{base}/h decreases, indicating that wave heights are reduced due to bottom friction and not depth-limited breaking. As bottom friction increases to the upper bound, the H_{base}/h ratio approaches zero. This reflects the exponential decay of wave height in response to increasing bottom friction. It should be noted that the wave model applied has not been validated for dissipation due to vegetation, because of the lack of data. Additional data is needed on waves in extreme events. Deployments during hurricanes Gustav and Ike during the 2008 hurricane season have obtained valuable data that, once analyzed, should improve our understanding of wave attenuation over wetlands.

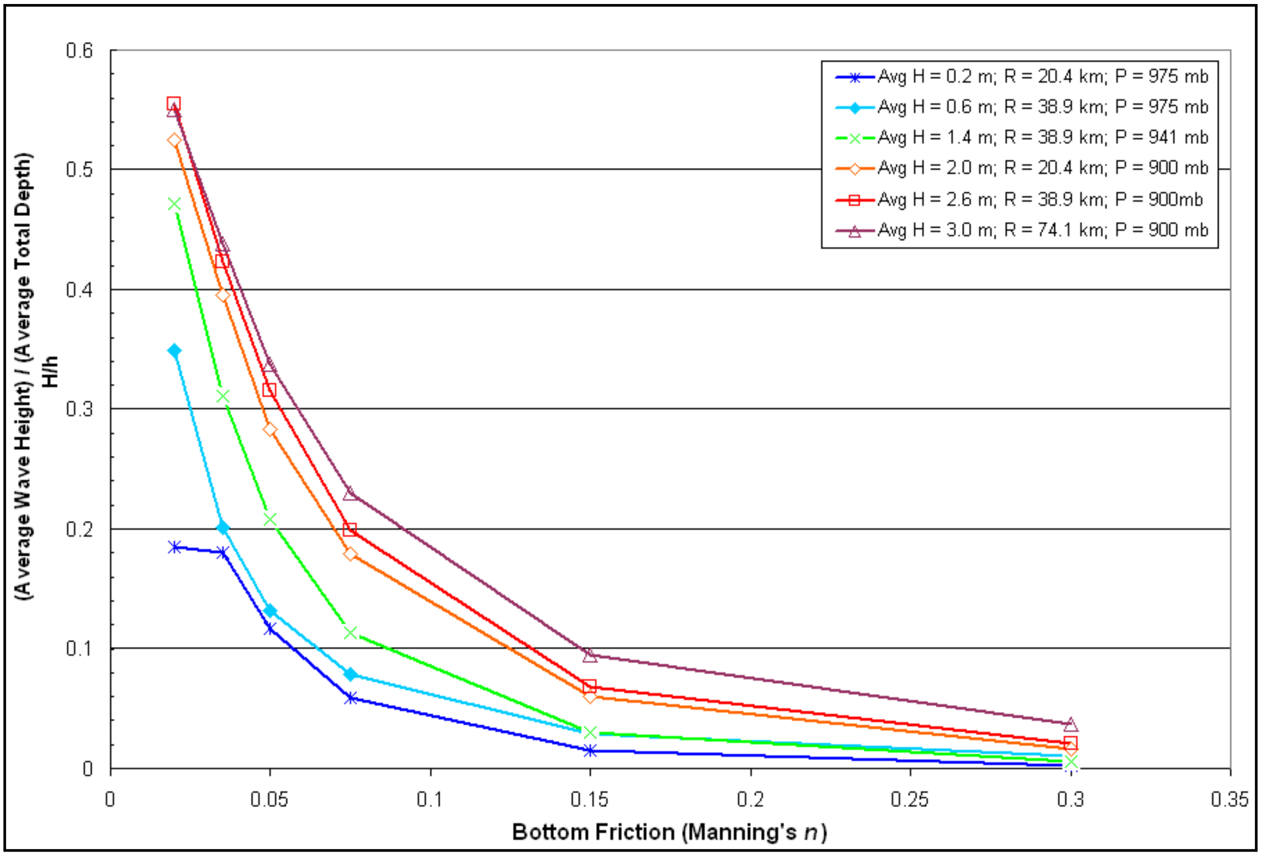

Figure 5. Ratio of peak wave height to average total depth within marsh (H_{base}/h) as a function of bottom friction within marsh.

Figure 6 depicts the relationship between bottom friction and the maximum percent change in peak surge along the coast. Up to a Manning's *n* of 0.075, low surge potential storms result in the greatest percent reduction in storm surge at the coast, while storms of high surge potential are associated with the smallest percent reductions in surge (with the exception of the storms producing 3.5 and 4.4 m of base surge, as explained in the previous paragraph). As surge potential increases, the relationship between maximum percent surge reduction and bottom friction becomes nearly linear. This is illustrated in Figure 6, as the storm of highest surge potential (purple line) is more linear than the storms of lower surge potential (blue, cyan, orange, and green lines). This effect is similar to that as described in Loder (2008) regarding the surge sensitivity to seabed elevation.

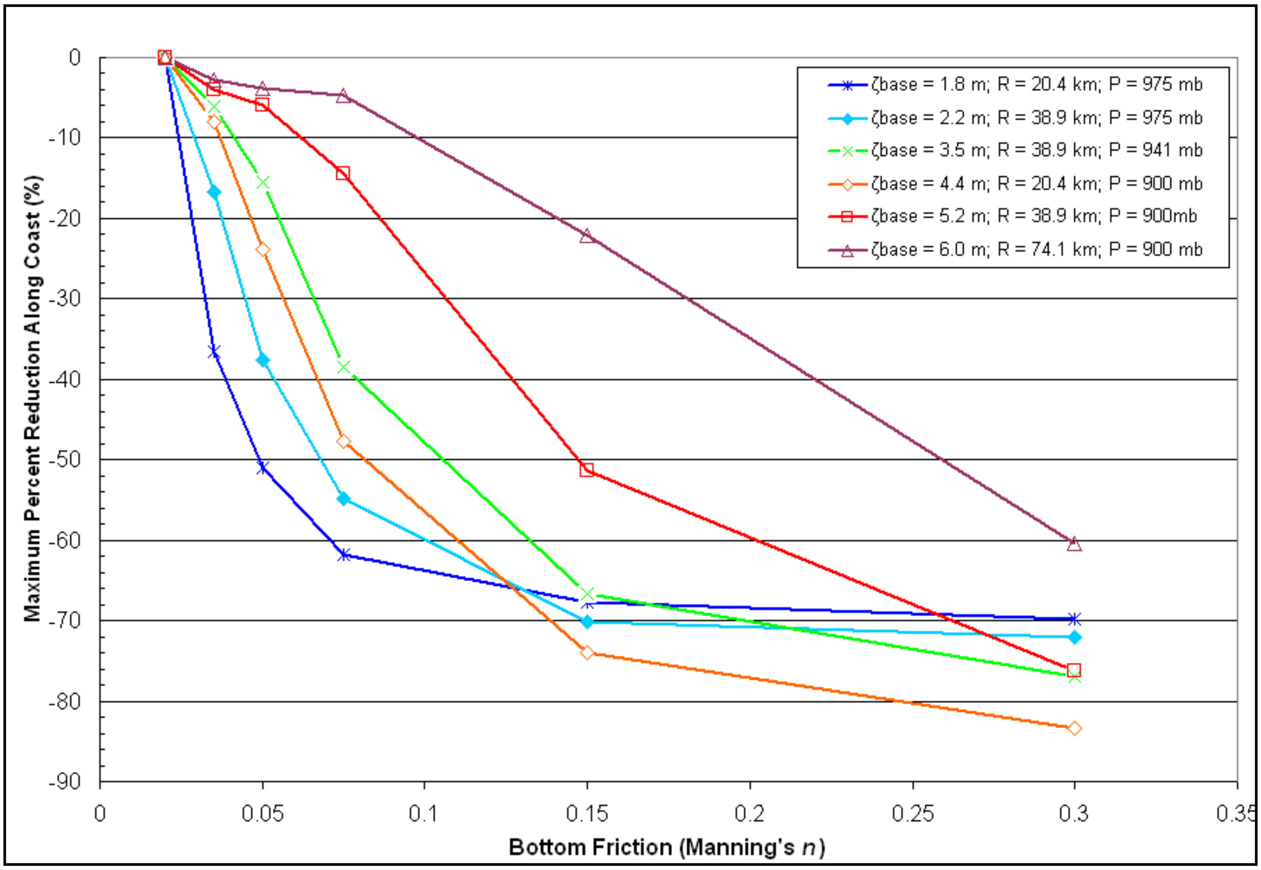

Figure 6. Percent change of peak surge at the coastline due to increased bottom friction.

SUMMARY: Within an area of increased bottom friction, storm surge levels are reduced due to the slowing of surge propagation through the marsh. In this study, an increase in bottom friction produces a decrease in surge elevation and a reduction in peak wave heights within an idealized marsh feature. The increase in Manning's *n* from 0.020 to 0.035 (range in Manning's *n* from open water to saline marsh, based on model validation) results in a 15 percent reduction in surge at the coast and a 0.4 m reduction in peak wave heights, given a storm of low surge and wave potential (ζ_{base} = 2.2 m, H_{base} = 0.6 m). As surge potential increases, the sensitivity of storm surge levels to increased bottom friction decreases. Results indicate that surge sensitivity to bottom friction is secondarily affected by the storm size due to the spread of surge along the coast.

It should be noted that the shelf slope and shoreline irregularity exerts great influence on the surge. The results presented here are from and idealized landscape where shoreline irregularities do not exist and only one shelf slope is considered. Ultimately, the potential of wetlands to attenuate surges is dependant not only on wetland characteristics (evaluated here), but also on the surrounding coastal landscape and the strength and duration of the storm forcing.

ADDITIONAL INFORMATION: Questions about this CHETN can be addressed to Mary A. Cialone (601-634-2139, email: *mary.a.cialone@usace.army.mil*). This Technical Note should be referenced as follows:

> Loder, N. M., M. A. Cialone, J. L. Irish, and T. V. Wamsley. 2009. *Idealized Marsh Simulations: Sensitivity of Storm Surge Elevation to Areas of Increased Bottom Friction*, Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN I-79. Vicksburg, MS: U.S. Army Engineer Research and Development Center. *http://chl.wes.army.mil/library/publications/chetn/*

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