ERDC/CHL CHETN-I-78
July 2009

US Army Corps of Engineers®

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

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PURPOSE: The purpose of this CHETN is to examine changes in peak surge elevation and wave height associated with changes in the elevation of an idealized coastal feature. 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 second 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 and waves to topographic and bathymetric change. Elevation is varied in the model simulations to represent the effects of seabed lowering (loss of marsh due to erosion, subsidence, or sea level rise) and indicates, in a qualitative sense, the degree to which a raised or lowered low-profile coastal feature may reduce storm surge elevation.

METHODOLOGY: A set of idealized surge simulations using ADCIRC (Westerink et al. 1992) and STWAVE (Smith et al. 2001) were conducted 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) and combinations of these variables. This note presents results for changes in elevation, while subsequent 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 gradients 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 gradients.

The idealized grid domain applied in this study includes 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). Elevation values range from $z = 0.5$ m above sea level to $z = 0.2$, 0.6, 1.8 and 3.0 m below sea level to represent the degradation from the approximate elevation of a typical marsh feature. Figure 2 depicts a typical cross section view of the idealized feature. Bottom friction is specified by Manning's *n*, which is held constant at an open water value of 0.020, approximately representative of a sandy surface with no vegetation (Chow 1959). Vegetation is not represented to isolate the impact of changing

seabed elevation. The coastal feature is backed by a non-overtopping wall that is representative of a levee.

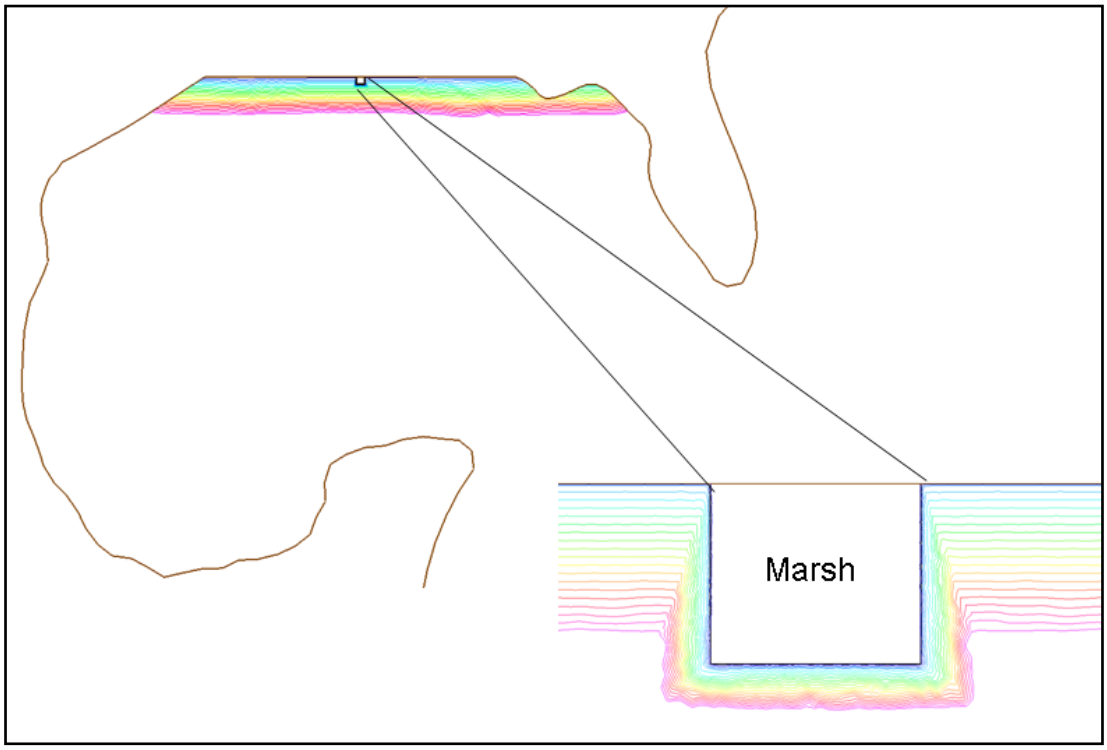

Figure 1. Idealized marsh-like coastal feature within the ADCIRC domain.

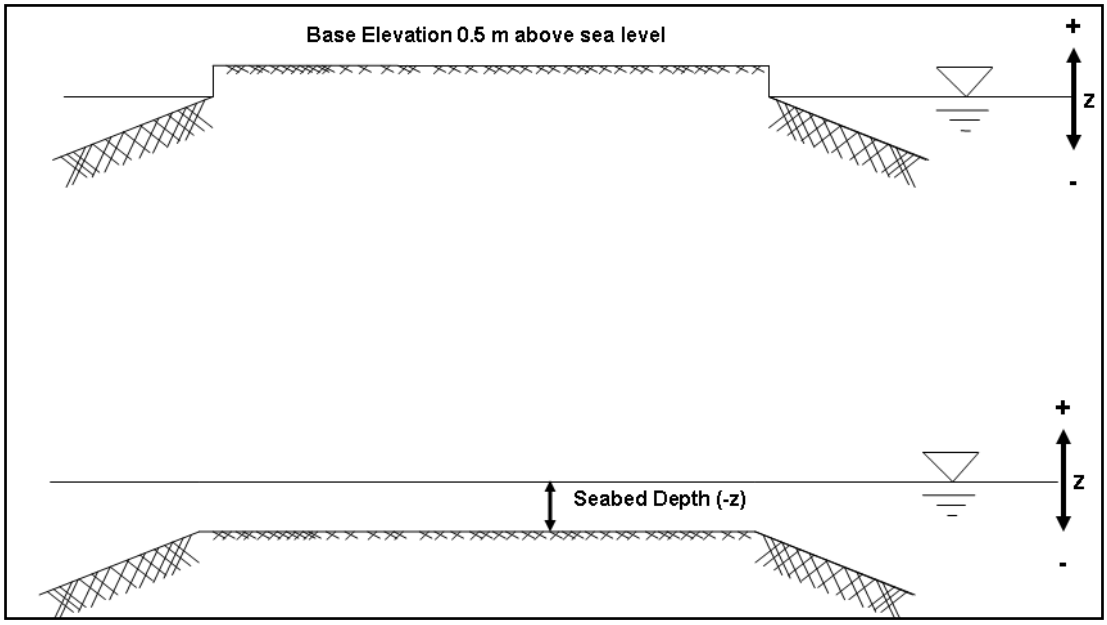

Figure 2. Sample cross section of idealized marsh-like feature. Top figure shows the base scenario, having a seabed elevation of 0.5 m above sea level. Bottom figure shows the experimental scenarios, having an elevation (z) ranging from -0.2 to -3.0 m relative to sea level.

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, which is related to the radius to maximum winds, range from 20.4 to 74.1 km. Table 1 also provides the surge and wave height potential for each storm which is the average peak surge or wave height over the marsh feature. The simulation of varying storm intensities and sizes provides insight into how bathymetric changes influence the surge and wave height for storms of varying intensities.

Table 1.
Storm Suite. Surge and Wave Potentials are Average Peak Conditions Within the Marsh Area

Landfall Pressure Radius (km)	Pressure at Landfall (mb)	Surge Potential, ζ_{base} (average peak surge for base configuration, m)	Wave Potential, H_{base} (average peak wave height for 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 show the peak surge and waves, respectively, for each of the six base simulations. In Figure 3, note the change in the slope of the surge across the marsh due to the sure increasingly piling up against the shoreline. Figure 4 shows the large wave energy dissipation that occurs at the fringe of the raised seabed elevation. Note also the lower wave heights on the left side of the raised seabed as waves are dissipated as they propagate from right to left. Figures 5 and 6 illustrate the sensitivity of surge and wave response to changes in nearshore seabed elevation. Figure 5 shows the percent difference in peak surge elevation from the base condition over the square marsh feature at an elevation z = +0.5 m above sea level, while Figure 6 depicts changes in peak wave height. Blue shading indicates decreases in peak surge (Figure 5) or wave height (Figure 6), while increases are indicated by red shading. The top left panel in Figure 5 depicts percent changes in peak surge levels due to the lowering of seabed elevation from 0.5 m above sea level to a depth of 0.2 m (z = -0.2 m). Figures 5 and 6 focus on effects within the boundaries of the idealized coastal feature. In areas outside the coastal feature, changes in surge response are less than 10 percent.

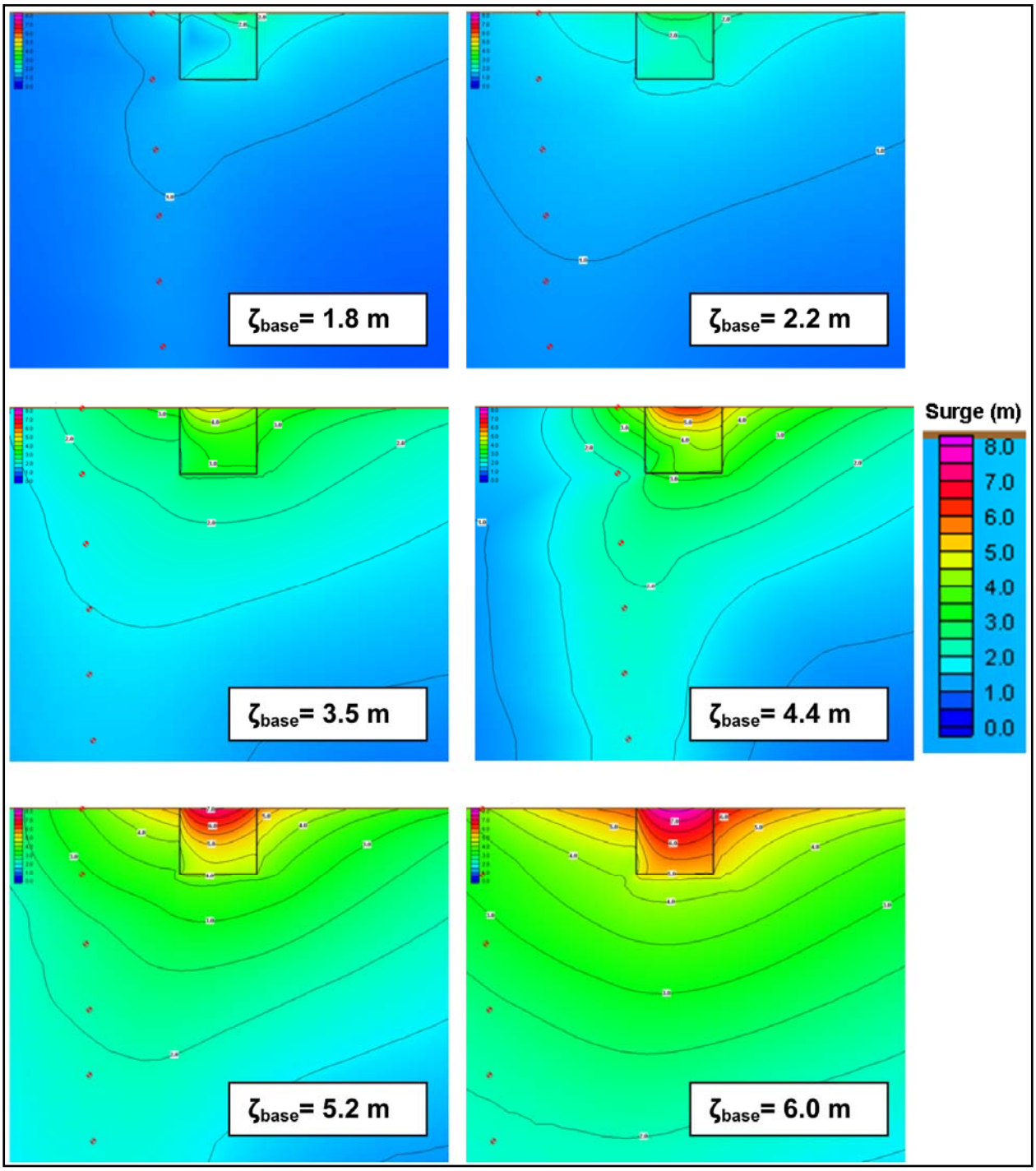

Figure 3. Peak surge on base condition for six storms.

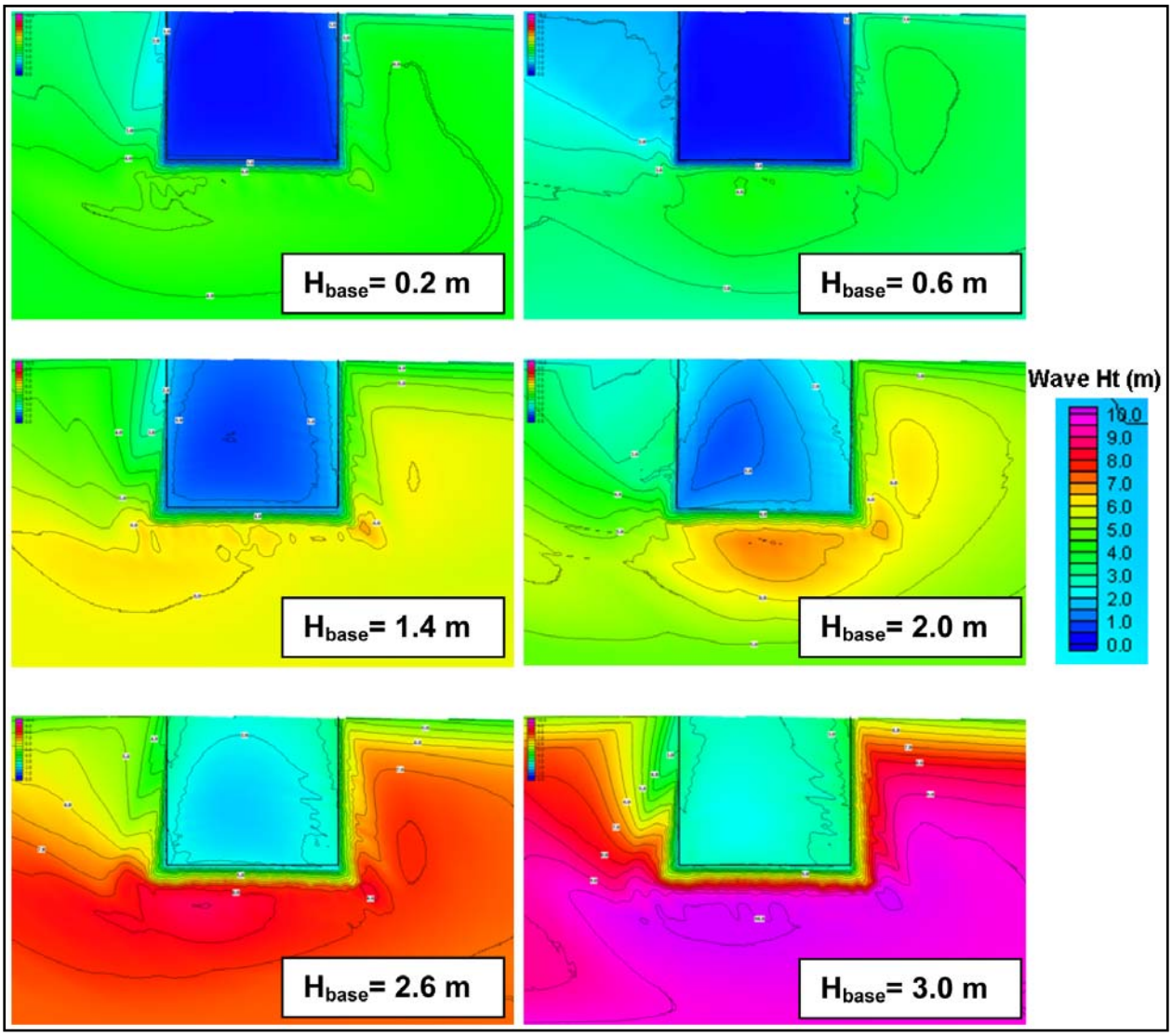

Figure 4. Peak wave heights on base condition for six storms.

Comparison of the surge results can be interpreted in terms of three factors: wave stresses, inverse relationship of surge gradient with depth, and bottom friction. Momentum from the wave field is transferred to the mean flow when the waves break, which drives a wave setup. Waves are depth limited in the marsh, so in the shallower the marsh, the waves break and force a setup in the breaking region. The shallowest marsh is in the base case, so for all other cases, the wave setup is less along the offshore and lateral boundaries of the marsh where the waves break. These differences are up to 15 percent for the least intense storm over the deepest marsh, but are generally 5 percent or less. The differences decrease as the marsh elevation is closer to the base case or the storms get stronger. For the larger, stronger storms, the magnitude of the total surge is much larger than the depth differences in the cases, so the modifications to the marsh have much less relative impact on wave stresses.

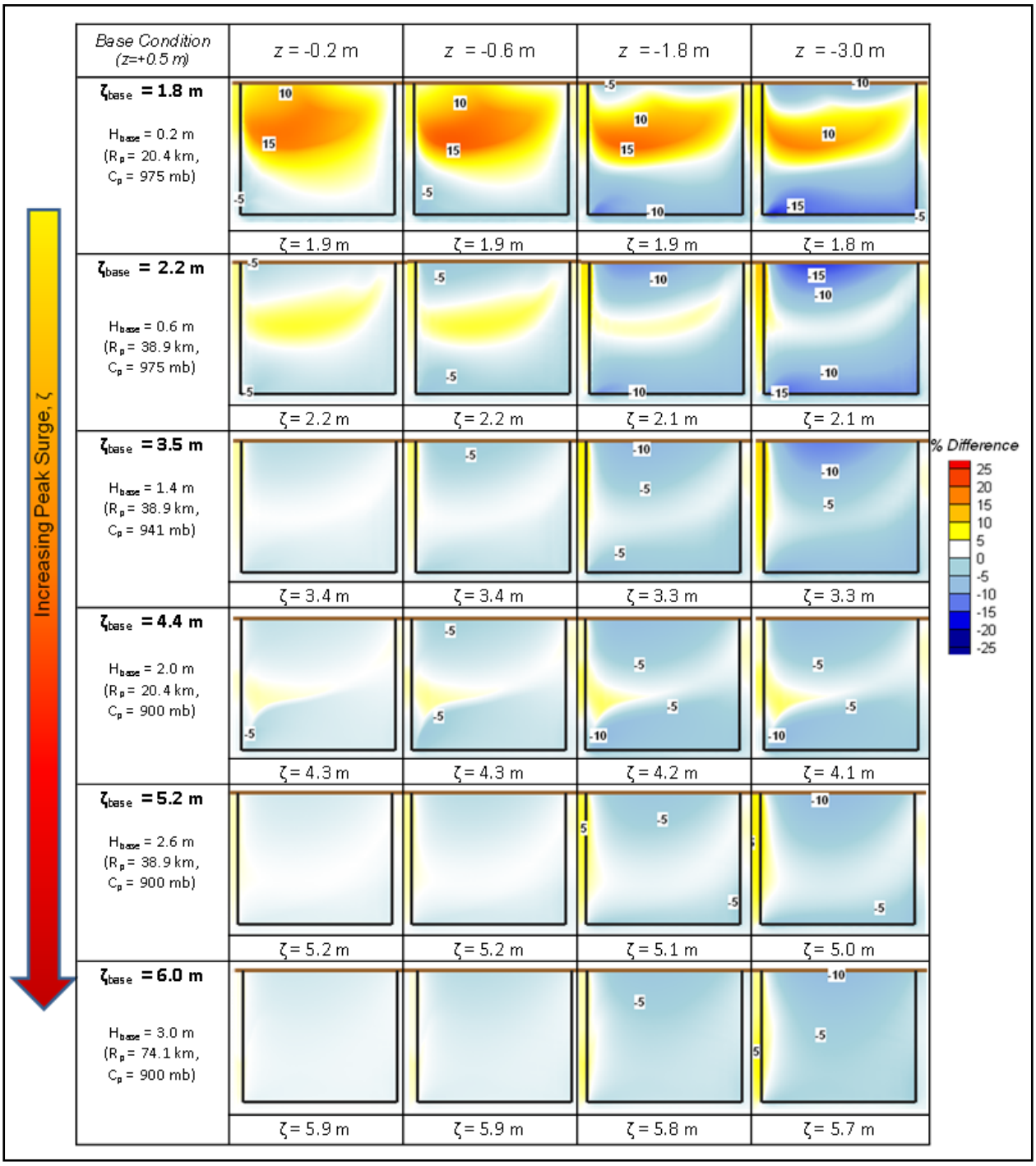

Figure 5. Percent change of peak surge response due to decreased elevation compared to an elevation of z = 0.5 m above sea level. Hot colors indicate surge increases, while cool colors indicate surge decreases, relative to the base condition. Top of square represents coastline. Average peak surge within each base case square is represented by ζ_{base}. Average peak surge within each experimental marsh square is denoted by ζ.

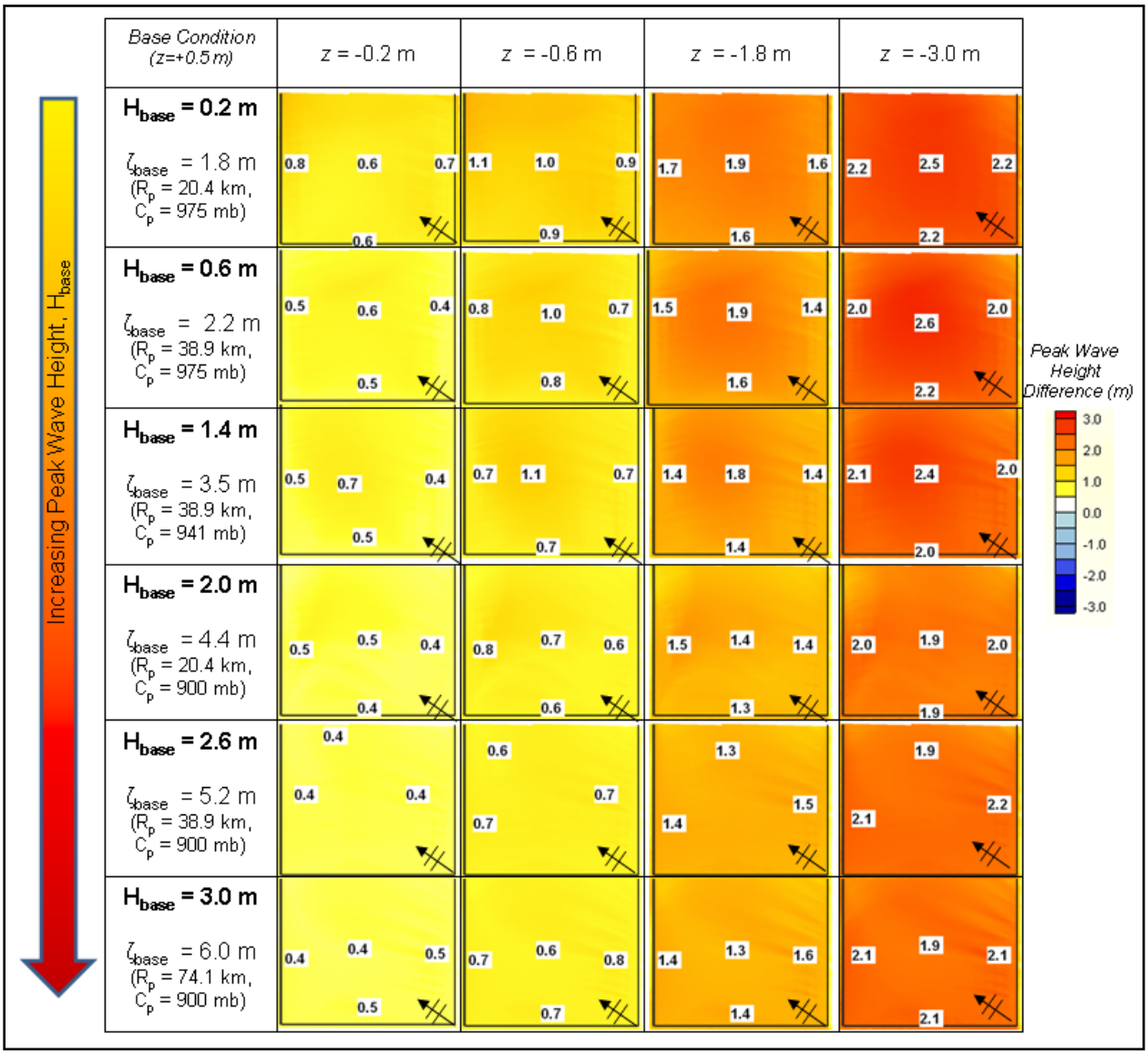

Figure 6. Change in maximum wave height (in meters) due to decreased elevation compared to an elevation of z = 0.5 meters above sea level. Hot colors indicate increased maximum wave height. Top of square represents coastline. Average peak wave height within the marsh is represented by H_{base}. Arrows indicate dominant direction of waves approaching the marsh.

Storm surge gradient is proportional to surface stress (τ) and inversely proportional to depth (*h*):

$$\frac{\partial \varsigma}{\partial x} \propto \frac{\tau}{h} \tag{1}$$

where τ is proportional to the wind speed squared plus the wave stress and *x* is the cross-shore direction. So, the second factor impacting the surge response to the marsh depth in a decrease in surge gradient as depth increases. The relationship in Equation 1 considers the most important terms in the momentum balance and neglects others such as friction. This is seen in Figure 5 as the plots get bluer from left to right (shallower to deeper marsh). Again, as the storms intensify,

the impact of the marsh depth is reduced as the magnitude of the surge becomes larger than the depth differences.

The final factor in the surge differences is bottom friction, which decreases as water depth increases, and surge propagation speed, which increases as water depth increases. These factors account for the two dimensionality shown in surge difference plots in Figure 5. The friction and propagation speed control both the filling and the draining of the marsh, so the shallower marsh fills slower and also drains slower. Also, the higher friction in a shallow marsh allows steeper surge gradients near the coast. The marsh fills due to wind forcing on the offshore and right side of the grid (counter clockwise winds) and water level gradients on all the open sides (right, left and bottom on the plots in Figure 5), but the lower friction and faster surge propagation for the deeper marshes will tend to speed the filling of the marsh and result in a higher water level in the center of marsh relative to the base case. This is most noticeable in the least intense storms, where the center of the marsh shows 10-15 percent increase in surge. Closer to the shore, the gradient in the surge is lower for the deeper marshes than the base case (due both to Equation 1 and lower friction), so the surge at the shoreline tends to be less than the base case (or at least less than at the center of the marsh). This stronger nearshore surge gradient occurs where the onshore wind pushes more water toward the coast than can flow laterally out of the marsh. For the more intense storms, this point moves further offshore. Again, as the storms become more intense and larger, the marsh depth becomes less of a factor in modifying the peak surge. Even in the case of this very simple marsh configuration, the response to changes in marsh depth is a complex combination of changes in wave and wind forcing terms and bottom friction.

It is interesting to note that the maximum peak surge values change only 5 to 10 percent between the base and deeper marsh cases, although, locally there are differences as large as 15 percent. In all cases except the z = -0.2 and -0.6 m marshes for the least intense storm, the surge at the shoreline was reduced for the deeper marshes.

Changes in wave height are focused within the marsh feature (Figure 6). Wave heights are uniformly increased with lowered seabed elevation. As the deepwater waves approach and enter the coastal feature, wave heights are reduced due to breaking. Since wave breaking is dependent upon depth, the elevation of the coastal feature has a direct impact on wave height within the marsh. In this way, wave heights within the marsh are decreased with decreasing depths due to depth-limited wave breaking. This effect is generally uniform throughout storms of varying wave potential.

Maximum wave heights are increased due to lowered seabed elevation. This is a result of wave heights being depth-dependent in the absence of vegetation. Figure 6 depicts a relatively uniform wave height response for storms of varying surge potential. Wave heights are increased by between 0.4 and 0.8 m due to a seabed lowered from 0.5 m above sea level to a depth of 0.2 m. For the extreme cases of seabed lowering, shown in the right-hand column of Figure 6, wave heights are increased by between 1.9 and 2.5 m. As stated earlier, storms of greater surge potential result in a more dramatic increase in wave height, as the total water depth is greater in these storms, allowing the waves to increase in peak height. Figure 7 depicts the relationship between average wave height and average total depth within the square feature as the seabed deepens. Storms of low wave potential (blue and cyan lines) induce wave heights that are small compared to total depth. As depth increases, a constant H/h is reached, indicating the wave height to depth

dependency. For storms of moderate and high wave potential (green, orange, purple, and red lines), the H_{base}/h factor is relatively constant, indicating that wave height development is limited by depth.

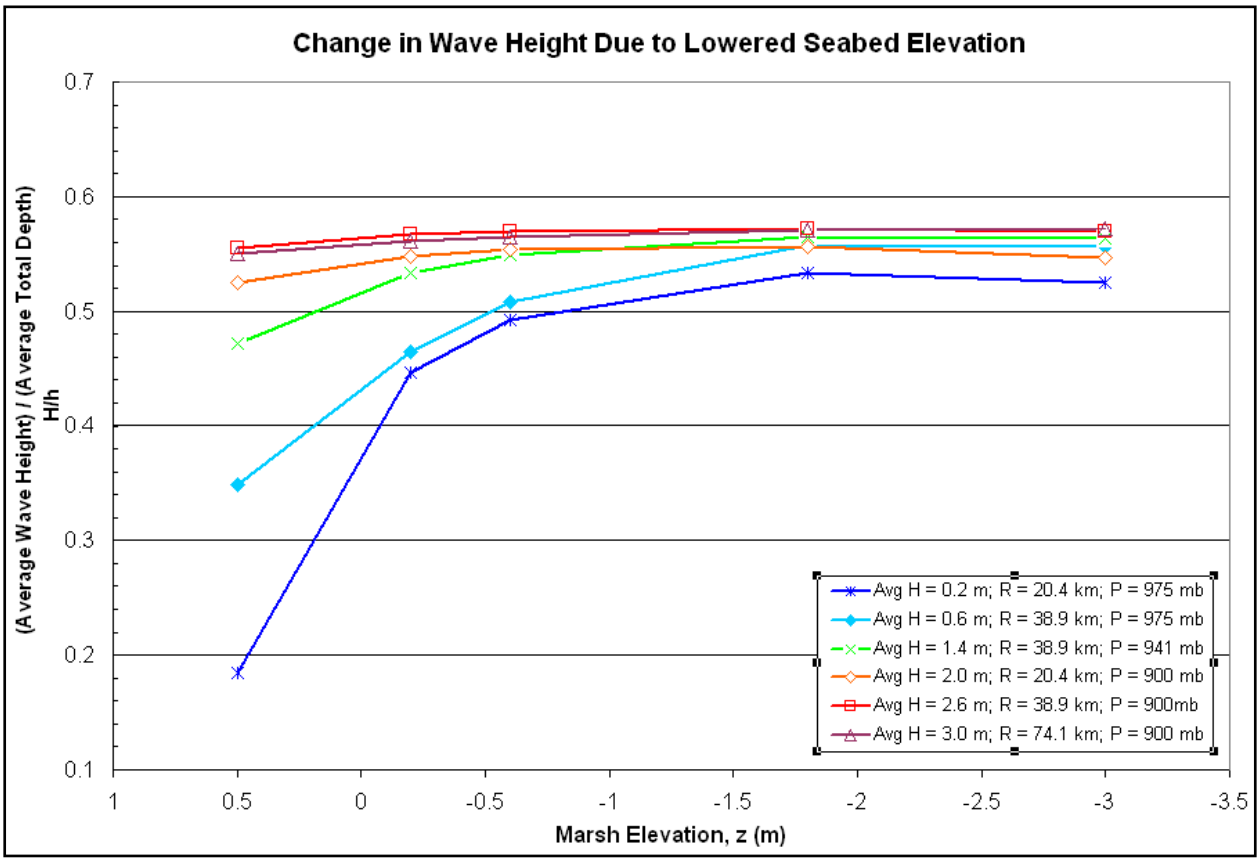

Figure 7. Ratio of average peak wave height within marsh square to average total depth within marsh (H_{base}/h) as a function of seabed elevation.

As surge potential increases, the surge levels become less sensitive to lowered bathymetry as extreme surge levels are less affected by bottom characteristics. Shoreward decreases in surge due to decreases in marsh elevation occur as a result of the inverse relationship between surge and water depth. Figure 8 indicates the relationship between coastal surge changes and marsh elevation. For a submerged marsh, similar relationships exist between surge changes and seabed elevation. With the four strongest storms in this study, it is shown that the relative effect of decreasing seabed elevation is dampened as surge potential increases. As surge potential increases, the relationship between seabed elevation and surge percent change approaches constant slope. This is indicated in Figure 7 by the red and purple lines, which represent events of high surge potential (ζ_{base} = 5.2 m and 6.0 m).

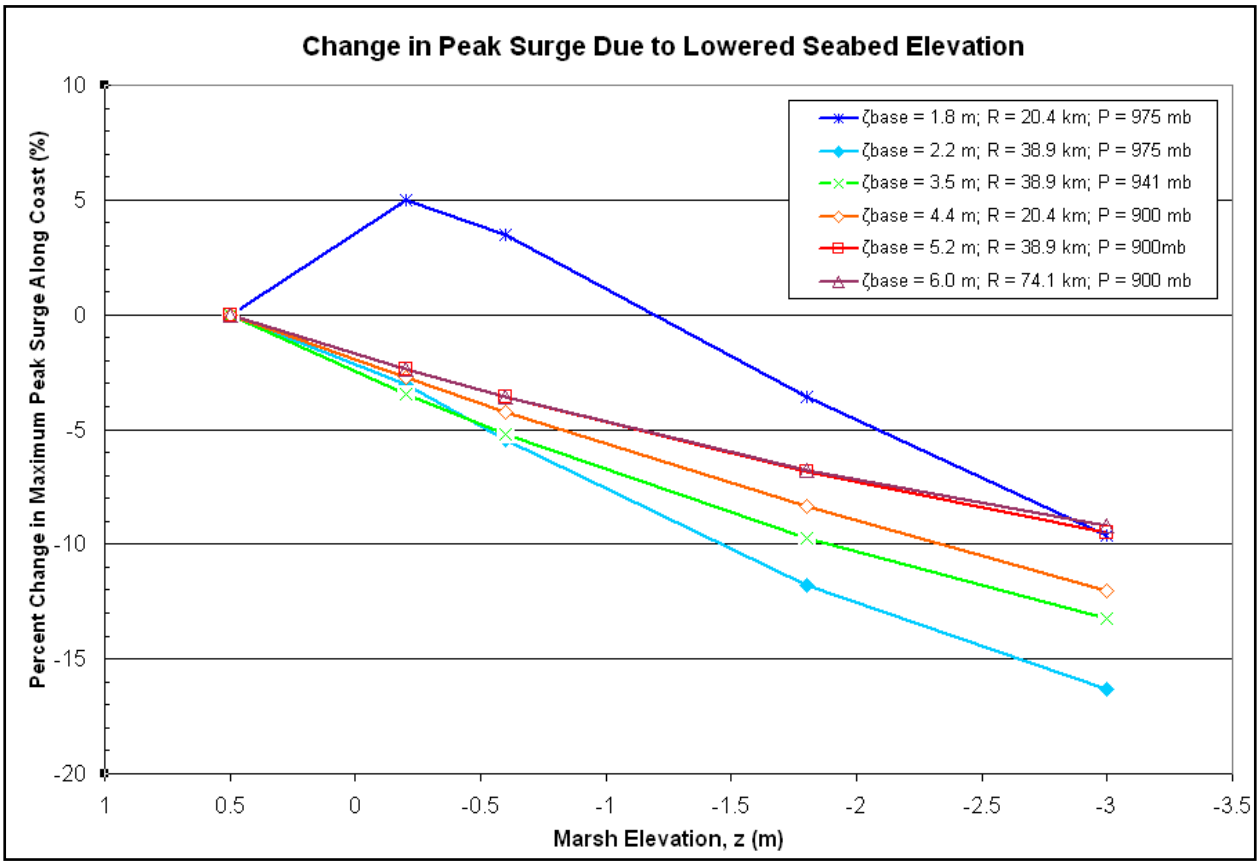

Figure 8. Percent change of peak surge due to seabed lowering.

SUMMARY: Due to the inverse relationship between storm surge and water depth, seabed lowering will generally result in reduced storm surge levels along the coast. With the exception of a storm event of low surge potential, results in this study confirm a relative decrease in surge levels due to decreased seabed elevation. There is a rise initially for the low surge potential storm because friction dominates at low water levels. A 5 to 15 percent decrease in surge levels at the coast and a 1.9 to 2.6 m increase in wave height are indicated for a marsh degradation of 3.5 m (from 0.5 m above sea level to 3.0 m below sea level). Although the surge is decreased, the higher wave height would increase wave setup, runup and overtopping on levees. Throughout the marsh area, a three part effect is observed with most of the simulated storms as the marsh depth is increased. The wave setup is decreased along the boundaries of the marsh as wave breaking is reduced in these areas. The surge gradient is decreased inversely with depth. Friction is reduced and surge propagation is increased, causing the marsh to fill and drain more quickly (generally increasing surge in the center of the marsh). Elevation impacts are most noticeable with storms producing the lowest surge levels. In terms of percent change in maximum surge along the coast, surge events of high potential are markedly less affected by seabed lowering.

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 seabed elevation. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-I-78. Vicksburg, MS: U.S. Army Engineer Research and Development Center. *http://chl.wes.army.mil/library/publications/chetn/*

ACKNOWLEDGEMENT: This work was supported by the Louisiana Coastal Area Science and Technology Program.

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