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The potential of wetlands in reducing storm surge

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ABSTRACT

A critical component of flood protection in some coastal areas is expected to be the potential contribution of wetlands to the lowering of surges as they propagate inland from the coast. Consequently, an accurate method to quantify the effect of wetlands on coastal surge levels is required. The degree to which wetlands attenuate surge is the subject of debate and difficult to assess. The potential of wetlands to reduce storm surge has typically been expressed as a constant attenuation rate, but the relationship is much more complex. A numerical storm surge model was applied to assess the sensitivity of surge response to specified wetland loss. Results suggest that wetlands do have the potential to reduce surges but the magnitude of attenuation is dependent on the surrounding coastal landscape and the strength and duration of the storm forcing. Numerical models that simulate the relevant physical processes can provide valuable information on how to best integrate wetlands into coastal protection plans. However, while the model applied for this study has displayed skill in estimating surges over wetlands, the formulations are missing key processes and model advancements are necessary.

1. Introduction

Coastal areas of the US are threatened by erosion and damage due to storm waves, wind, and surge. The risk of damage and loss of life is exacerbated by many factors, including coastal development, sea level rise, coastal subsidence, and loss of environmental habitat such as wetlands that may provide natural protection from storm damage and erosion. As the 2005 and 2008 hurricane seasons illustrated, the potential societal and economic consequences of coastal protection decisions can be wide-spread and enduring. Design of coastal protection systems must be based on a regional, holistic approach to storm surge and wave mitigation, in which both engineered and natural features, such as wetlands, are considered. It is generally acknowledged that wetlands have the potential to reduce surge and waves, but the degree to which they do is the subject of debate and difficult to assess. Understanding the interaction between hurricanes and wetlands is necessary in planning hurricane flood protection for low lying delta areas such as South Louisiana.

The potential of wetlands to reduce storm surge has typically been expressed by empirical rules of thumb based on observations. These simple rules of thumb assume a constant attenuation per width of marsh. The true attenuation is much more complex and dependent on many physical factors including storm intensity, track, forward speed, and the surrounding local bathymetry and topography. Resio and Westerink (2008) warn that the application of a constant attenuation rate can be misleading because it does not account for the transient nature of forcing or the local topographic/bathymetric conditions. Complicated coastal geometries and the complex forcing of hurricanes, however, can be simulated with numerical models that properly define the physical system and include all the primary processes, including winds, air–sea momentum transfer, atmospheric pressure, wind-driven waves, riverine flows, tides, and friction (Bunya et al., 2009).

The purpose of this study is to understand the storm surge reduction potential of wetlands. Previous studies that have measured inland surge propagation are briefly reviewed and recent measurements from Hurricane Rita are analyzed. A high-resolution numerical storm surge model was applied to assess the sensitivity of surge response to specified wetland loss. The analysis is limited to hurricane surges, but wetlands also influence storm waves. Results of a previous numerical study (Wamsley et al., 2009) indicated that wave change patterns are consistent with water level changes, suggesting depth-dependent breaking. Vegetation increases friction and wave attenuation and may reduce wave setup (Dean and Bender, 2006). The impact of wetlands on storm waves is mostly unknown and difficult to accurately quantify given the lack of data and detailed knowledge about the physics of these processes. Literature on wave attenuation in wetlands is limited to relatively small waves in either emergent or just submerged conditions (e.g., Knutson et al., 1982; Moller, 2006; Augustin et al., 2009). A recent deployment of wave gauges in wetlands for Hurricanes Gustav and Ike may provide some much needed data to address this issue.

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A criticalcomponentoffloodprotectioninsomecoastalareasisexpectedtobethepotentialcontribution ofwetlandstotheloweringofsurgesastheypropagateinlandfromthecoast.Consequently,anaccurate methodtoquantifytheeffectofwetlandsoncoastalsurgelevelsisrequired.Thedegreetowhichwetlands attenuatesurgeisthesubjectofdebateanddifficulttoassess.Thepotentialofwetlandstoreducestorm surgehastypicallybeenexpressedasaconstantattenuationrate,buttherelationshipismuchmore complex.Anumericalstormsurgemodelwasappliedtoassessthesensitivityofsurgeresponseto specifiedwetlandloss.Resultssuggestthatwetlandsdohavethepotentialtoreducesurgesbutthe magnitudeofattenuationisdependentonthesurroundingcoastallandscapeandthestrengthand durationofthestormforcing.Numericalmodelsthatsimulatetherelevantphysicalprocessescanprovide valuableinformationonhowtobestintegratewetlandsintocoastalprotectionplans.However,whilethe modelappliedforthisstudyhasdisplayedskillinestimatingsurgesoverwetlands,theformulationsare missingkeyprocessesandmodeladvancementsarenecessary.

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2. Observations

The constant attenuation rate rules of thumb are based on empirical data with a high degree of scatter. This is expected because of the complex process of inland surge propagation and the difficulty in obtaining measurements that best characterize the influence of landscape features and vegetation. A commonly stated rule of thumb is based on a US Army Corps of Engineers report that correlated storm surge elevations with distance inland from the coast for seven storms occurring across Southern Louisiana between 1909 and 1957 (Corps of Engineers, 1963). Inconsistent results were obtained when attempting to correlate hurricane translation speed, surge hydrograph at the coast, and surge elevations inland. However, a trend was observed for the decrease in storm surge as a function of distance inland. The relationship indicates that storm surge was reduced by 1 m for every 14.5 km inland, but a close inspection of the data reveals a large degree of scatter. When the data are grouped by storm, attenuation rates for these storms range from 1 m per 60 km to 1 m per 5 km (differing by a factor of 12).

Lovelace (1994) documented storm surge elevations measured during the second landfall of Hurricane Andrew, which occurred in the vicinity of Point Chevreuil, Louisiana, on August 26, 1992. Gauge data from Cocodrie, Louisiana indicated a maximum water elevation of 2.8 m for this Category 3 Hurricane. Over a 37 km stretch of marsh and open water from Cocodrie to the Houma Navigation Canal, the water elevation decreased from 2.8 to 1 m, equating to a reduction in surge amplitude of 1 m per 20 km of marsh and open water. A similar set of measurements showed reduction of the storm surge from 1.5 m at Oyster Bayou to 0.15 m at Kent Bayou, located 30.6 km north. This second set of measurements indicated a 1 m decrease in surge per 23 km over fairly continuous marsh.

In 2005, less than one month following the landfall of Hurricane Katrina, Hurricane Rita made landfall near the Louisiana and Texas border, with extensive inland surge penetration. A relatively large data set was measured during Rita. In addition to 80 high water marks (HWM) that were deemed to be good quality and due only to storm surge (no wave effects), the United States Geological Survey (USGS) collected data from 23 water level sensors deployed across western Louisiana (McGee et al., 2006). These data were culled to identify locations with the most ideal measurements. Ideal measurements are those that are (1) in line with the path of the storm, (2) on the same side of the storm, (3) not so far apart that processes (e.g., barometric pressure, winds, rainfall) are significantly different, (4) representative of a homogeneous landscape feature, and (5) not influenced by man-made features such as levees, roads, canals, or other water bodies. Four profile locations were deemed acceptable and observations are summarized in Table 1. The measured surge attenuation rates varied from 1 m per 25 km to 1 m per 4 km.

3. Modeling

The large range in observed attenuation rates suggests that the physics of surge propagation over wetlands is more complex than can be described by a constant rate. The enhanced roughness of wetlands can slow the advance of storm surge, which increases water levels seaward of the wetland and reduces the surge, or delays its arrival time, landward of the wetland. These processes may retard the storm propagation in one area, but as they slow storm surge advance, the movement of water may be redirected toward another location, causing a local storm surge increase. Wetlands do not decrease the mass of water driven by the storm; they change the momentum and redistribute the surge. The complex interaction of the storm and wetlands is dependent on the intensity, track, and forward speed of the storm, as well as wetland vegetation type, density, and height, and the surrounding local bathymetry and topography. This complex interaction can be simulated with a recently developed surge model for South Louisiana.

Considerable advancements in storm surge modeling have been made since the 2005 hurricane season. Westerink et al. (2008) and Bunya et al. (2009) document the development and validation of a high-resolution coupled riverine flow, tide, wind, wave, and storm surge model for South Louisiana. The integrated modeling system accurately represents the physical system with resolution as fine as 50 m and includes the nonlinear coupling of multiple processes that contribute to storm surge. For synthetic storms, the TC96 Planetary Boundary Layer (PBL) model (Thompson and Cardone, 1996) is applied to construct a time series of wind and atmospheric pressure fields for driving surge and wave models. For hindcasts of historical storms, the winds are constructed using data assimilation techniques as described by Bunya et al. (2009). The storm surge is modeled with ADCIRC (Advanced CIRCulation) (Luettich et al., 1992; Westerink et al., 1994; Luettich and Westerink, 2004) which computes the pressure- and wind-driven surge component. In parallel with the initial ADCIRC simulation, the large-domain, discrete, time-dependent spectral wave generation model WAM (Wave Model) (Komen et al., 1994) calculates directional wave spectra that serve as boundary conditions for the near-coast STeady-state spectral WAVE (STWAVE) model (Smith et al., 2001; Smith and Sherlock, 2007). STWAVE calculates wave generation and transformation on the shelf and within the wetlands, including the depth variation due to surge. The radiation stress (momentum imparted on the water column due to the waves) fields calculated by STWAVE are passed to ADCIRC which is rerun for the time period when the radiation stresses make a significant contribution to the water levels, providing a final estimated water level.

Wetlands are represented in the coupled numerical models by bathymetric and frictional resistance. Wetlands can reduce surge potential through bathymetric resistance, slowing the surge propagation due to the shallow depth, through bottom friction

Table 1
Observed wetland attenuation rates for Hurricane Rita (developed from McGee et al., 2006).

Profile location	Profile start			Profile end			Surge attenuation rate (m/km)
	Lat.	Lon.	Surge Elv. (m)	Lat.	Lon.	Surge Elv. (m)	
Cameron Prairie	29.786	−93.107	4.1	29.815	−93.106	3.7	−1/10
Sabine	29.765	−93.764	3.3	29.803	−93.753	2.3	−1/4
Vermillion	29.825	−92.126	3.4	29.866	−92.127	3.1	−1/25
Vermillion	29.783	−92.193	3.3	29.847	−92.241	2.6	−1/13

dissipating energy, and through reduction of surface winds. Winds are reduced in the coupled models through a directional masking procedure to account for the greater surface roughness. In addition to reducing wind speeds, the models eliminate the wind stress in forested wetlands which inhibit wind from penetrating to the water surface. Westerink et al. (2008) provides a detailed discussion of the atmospheric forcing adjustments. The speed at which the storm surge propagates is affected by wetlands through bottom friction and form drag. Bottom friction is generated by fluid shear stresses at the bed and flow drag resistance is generated by fluid stresses on vegetation extending through the water column. Bottom friction is important in relatively shallow areas, and bottom friction and flow drag resistance are enhanced in vegetated areas. The coupled models presently employ a standard quadratic parameterization of bottom stress with a Manning's n type formulation. Westerink et al. (2008), Bunya et al. (2009) and Wamsley et al. (2009) provide a complete discussion of the frictional formulations and parameterizations applied to represent the effect of vegetated wetlands on the wind boundary layer and bottom friction.

The Manning's n approach may not be the most appropriate method to account for energy and momentum losses due to vegetated features. The actual resistance to flow is not only through bottom friction but also from the form drag of plant stems, branches, etc., particularly when the vegetation is emergent. The effect of form drag is only being approximated by increasing the bottom friction coefficient. In addition, the effects of sub-grid scale channels in wetlands are not resolved in the surge model. Despite these limitations, the coupled modeling system has been validated with data from Hurricanes Katrina and Rita and compare well with observed HWMs, with a standard deviation of approximately 0.4 m. Specifically, the comparisons to hydrographs from Hurricane Rita demonstrate that the model system captures both the forced surge increase and the flood recession process at far inland stations, indicating that the friction due to wetland vegetation is reasonably represented. Bunya et al. (2009) provide details on the model validation.

The validated integrated modeling system was applied to perform a sensitivity analysis to investigate the role of wetlands in attenuating storm surge. Simulations were made for a base condition landscape configuration in South Louisiana and an estimated future condition landscape. The role of wetlands in coastal protection was investigated by comparing peak computed water levels for the base and future wetland conditions across two wetland areas in Southeastern Louisiana.

4. Wetland characterization

Wetlands are represented in the numerical model by bathymetric and frictional resistance. Topography in the wetlands, where measured elevation data is typically not available, was estimated from land cover data sets and assigned typical topographic heights for marshland as provided by the National Wetland Research Center (2004). The base configuration is consistent with the land cover type taken from the USGS National Land Cover Dataset (NLCD) classification raster map based upon Landsat imagery and the USGS Landsat Data Gap study. The Landsat imagery data are from the 1990s (Vogelmann et al., 2001). The Gap data divide the coastal marshes based on salinity into four vegetation zones: fresh, intermediate, brackish, and saline as described by Chabreck (1972). Visser and Sasser (1998) identified 12 vegetation types that occur under the salinity regimes in coastal Louisiana. These vegetation types plus the swamp and bottomland hardwood types are distributed throughout Southern Louisiana (Steyer et al., 2003). Ten of these vegetation types are found across the Caernarvon and Barataria marsh profiles that are analyzed for this study (see Fig. 1). The Caernarvon marsh is located east of the Mississippi River with the river levees bordering the marsh to the west and south. Barataria is west of the river and south of New Orleans. Highway 90 borders the north end of this profile. The Barataria wetland profile is characterized by non-continuous marsh that crosses Little Lake and Lake Salvador and includes a swamp on the northern end of the profile near Highway 90.

Polyhaline oystergrass is the common saline marsh vegetation type and is always dominated by *Spartina alterniflora*. The brackish marsh is classified as a mesohaline mix and includes the *Distichlis spicata* and *Spartina patens* species. The intermediate marsh is divided into oligohaline wiregrass and the oligohaline mix. The fresh marsh is composed of fresh bulltongue, fresh maidencane, and fresh cutgrass vegetation types. Visser et al. (1998) and Visser and Sasser (1998) provide a complete discussion of the various vegetation types and species.

For computing wind reduction, a single land roughness length ($z_{0-land} = 0.110$ as defined by the Federal Emergency Management

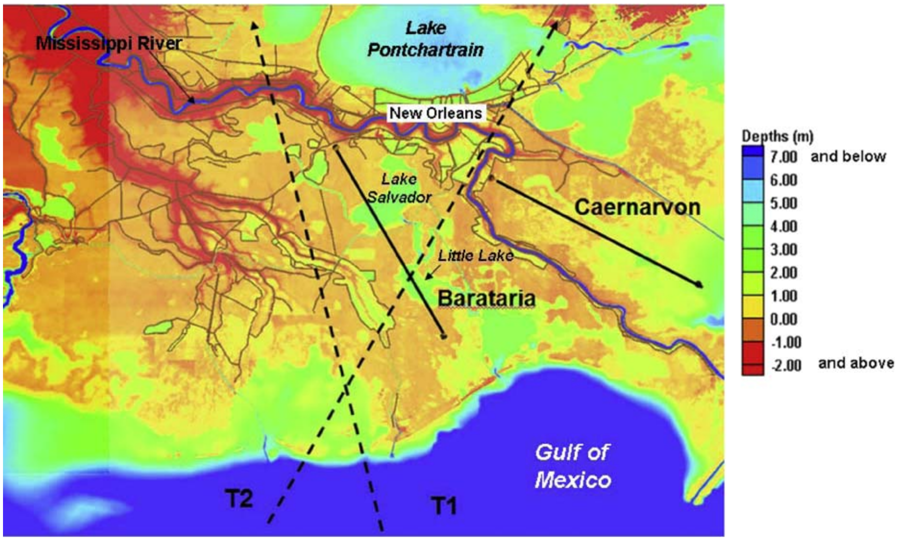

Fig. 1. Study area map. Solid black lines represent wetland analysis profile locations, dashed black lines are the approximate storm tracks near landfall.

(FEMA) HAZUS program (FEMA, 2005)) was assigned for the four herbaceous wetland vegetation zones. For parameterizing the hydraulic friction in the wetlands, the Manning *n* value was specified based upon the Gap classification to account for the different vegetation types in the various salinity regimes. The Manning *n* values were based on values found in standard hydraulic literature and validated through comparison of model hindcast results and measured HWMs for Hurricanes Katrina and Rita as described by Bunya et al. (2009). The Manning *n* values assigned for the four marsh types and open water are given in Table 2.

Manning *n* values are incorporated into the ADCIRC and STWAVE grids at the appropriate scale. The NLCD and Gap data sets define land cover on a 30 m averaging scale. The unstructured ADCIRC grid resolution varies from about 50 m in channels to approximately 50 km in the deep Atlantic Ocean. The STWAVE grid has a 200 m resolution. Therefore, the Manning *n* value assigned at a given node is the average of all values in the land cover data set within a nodal control volume that is determined by the grid resolution at that location. Applying this approach, an area of ''patchy'' marsh has a lower Manning *n* value assigned than that given in Table 2 to account for the segmentation by open water. The values in Table 2 are characteristic of a healthy continuous marsh area. The computed base configuration Manning *n* values for the Caernarvon and Barataria basins are plotted in Fig. 2. The Caernarvon wetland profile progresses from open water to a saline marsh on the seaward side, transitioning to a brackish marsh area closer to the levee system. The Barataria wetland profile is saline seaward of Little Lake. On the landward side of Little Lake is an intermediate marsh that transitions to fresh marsh. The marsh landward of Lake Salvador is also fresh with some intermediate marsh areas. The land cover at the northern end of the Barataria profile near Highway 90 is swamp.

Table 2
Manning *n* values for Louisiana wetland types (see Fig. 2).

Wetland type	Manning *n* value
Saline	0.035
Brackish	0.045
Intermediate	0.050
Fresh	0.055
Open water	0.020

To investigate the potential increase or decrease in surge due to changes in coastal marshes, modifications to the bathymetry grid and surface roughness were made based on future landscape predictions from the Coastal Louisiana Ecosystem Assessment and Restoration (CLEAR) model (Twilley, 2003). The CLEAR model is a coastal forecast system that predicts physical processes, geomorphic features, water quality, and ecological succession. Geomorphic/bathymetric changes are based on the likelihood of discretized regions changing from open water to marsh or marsh to open water. The CLEAR system was applied to predict a wetland definition 50 years into the future, which considers the impact of sea level rise on wetland loss (for a discussion of the impact of sea level rise on surges, see Smith et al., 2009), assuming no additional coastal restoration activities are undertaken. Degradation is predicted across most of Southern Louisiana, but there are isolated areas of growth in the Atchafalaya basin and Breton Sound in the Caernarvon marsh area. The accuracy of these predictions is outside the scope of this paper. The results are applied to define a specified future condition for the purpose of assessing the sensitivity of peak surge levels to wetland loss. Fig. 3 plots the future landscape bathymetry changes from the base condition. While the CLEAR projection includes landscape changes other than coastal marshes, the analysis for this study is limited to coastal marsh changes in the Caernarvon and Barataria areas. These marsh areas were reduced in elevation by as much as 1 m across large areas. The land roughness and Manning *n* values were also updated at the appropriate grid scale based on the predicted changes in land cover type. Fig. 4 plots the Manning *n* values across the Caernarvon and Barataria profiles for both the base and future conditions. The estimated future condition across Caernarvon includes deepening in open water and marsh degradation on the seaward side of the marsh and an area of land building from the Caernarvon diversion project. The diversion project creates fresh marsh near the river levees and transitions much of the brackish marsh to intermediate further seaward. At Barataria, degradation is predicted across the profile. Much of the saline marsh seaward of Little Lake becomes open water and the fresh marsh seaward of Lake Salvador transitions to intermediate and brackish marsh.

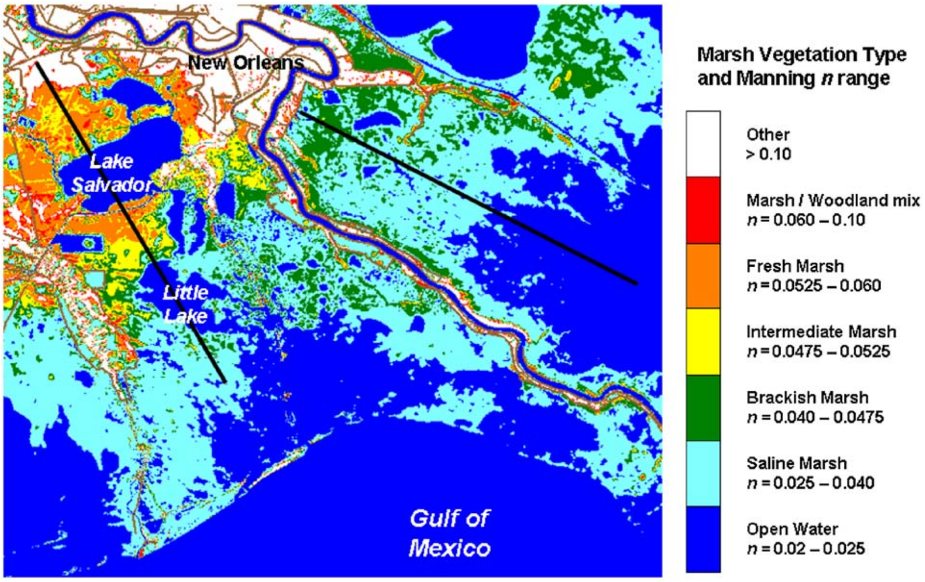

Fig. 2. Manning *n* values of various marsh types for base configuration. Solid black lines indicate approximate location of analysis profiles.

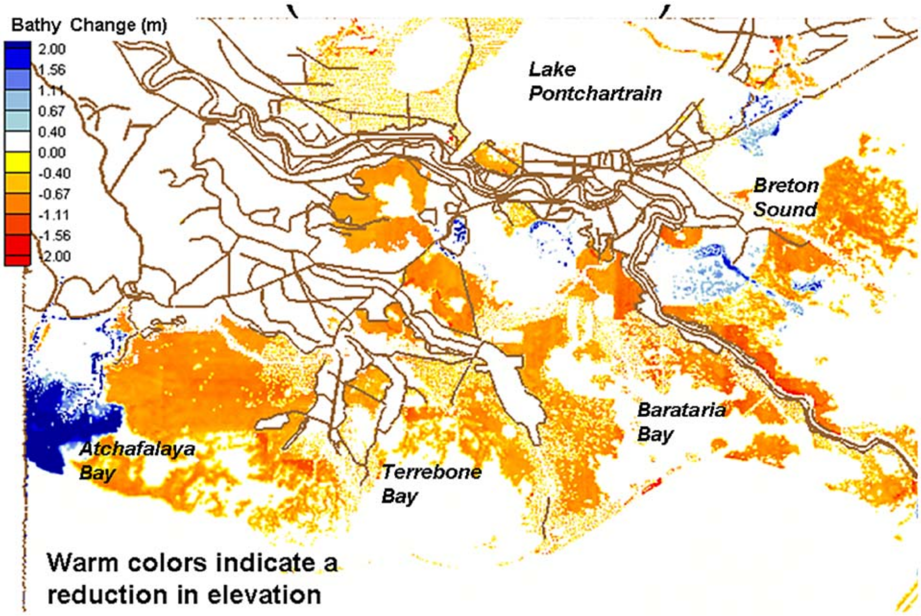

Fig. 3. Future CLEAR/NIA landscape bathymetry changes form the base condition (future condition–base condition).

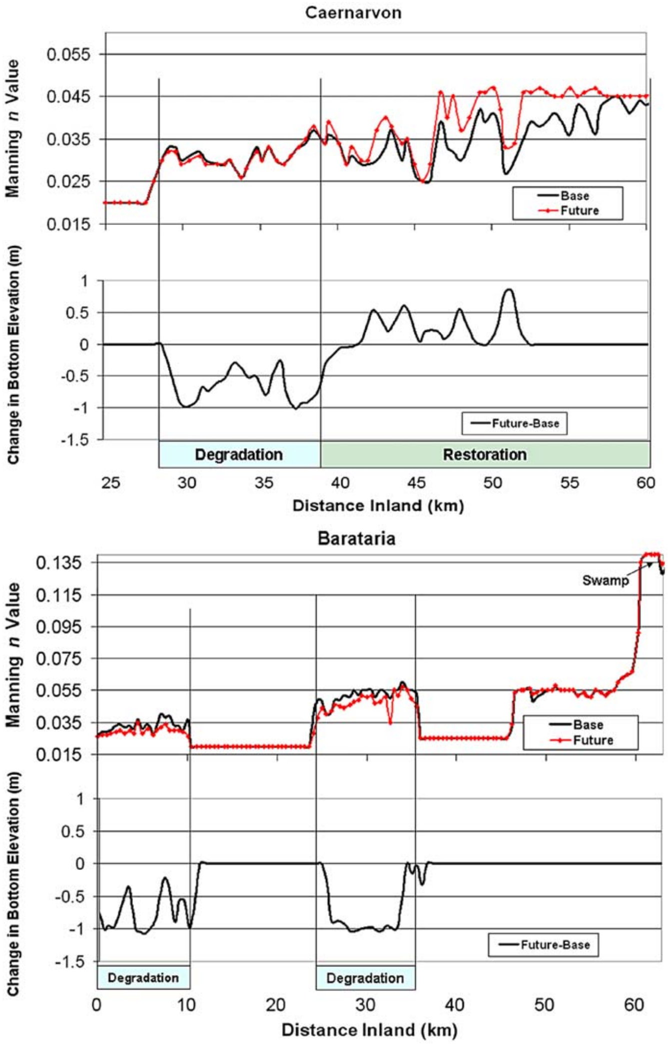

Fig. 4. Manning *n* values across the Caernarvon and Barataria wetland profiles for the base and future conditions. Bottom elevation change between the future and base conditions (future–base) is also plotted.

5. Analysis

The role of wetlands in coastal protection was investigated by comparing peak water levels computed by the integrated numerical modeling system for the base and future wetland conditions. To evaluate the influence of storm intensity, track, forward speed, and local bathymetric conditions on the surge attenuation potential of a wetland, four synthetic storms were simulated and peak water levels across two wetland areas at Caernarvon and Barataria in Southeastern Louisiana were analyzed. The Caernarvon and Barataria marshes are located east of the storm landfall locations (see Fig. 1). The characteristics for the four storms simulated are summarized in Table 3, and the approximate tracks near landfall are plotted on Fig. 1. A peak surge plot for the base condition for each storm is given in Fig. 5 and peak surge in each wetland area analyzed is tabulated in Table 3. The influence of storm intensity is evaluated by comparing storms S1 and S2 (central pressure of 960 and 900 mb, respectively). Comparison of S1 and S3 isolates how forward speed influences the effectiveness of wetlands to attenuate surge (forward speeds of 5.1 and 3.1 m/s, respectively); analysis of S2 and S4 provides insight into how the storm approach to the coast (i.e., landfall angle, northwest and northeast, respectively) influences surge propagation across wetlands.

Fig. 6 plots the surge or water surface elevation (WSE) relative to NAVD88 across the Caernarvon and Barataria base condition marsh profiles identified in Fig. 1 for all storms in the sensitivity suite. The bathymetric/topographic profiles for both the base and future conditions are also plotted. Fig. 6 illustrates how the same storm can result in different surge responses across wetlands depending on the surrounding coastal landscape. At Caernarvon, the surge increases from the seaward edge of the marsh (approximately a cross-shore distance 29 km along the profile) to the hurricane protection levee at the end of the profile for all storms analyzed. The magnitude of surge increase over the 31 km of wetlands ranges from 0.7 m (Storms S1 and S4) to 1.8 m (Storm S2). For the same storms, the surge decreases across Barataria. The decrease in surge over the 34 km from the start of the profile to the Gulf Inter-coastal Waterway (GIWW) ranges from 1 m (Storm S1) to 2.5 m (Storm S4). A contributing factor in the different

Table 3
Sensitivity analysis storm suite.

Storm	Central pressure (mb)	Rmax (km)	Forward speed (m/s)	Track (see Fig. 1)	Peak surge Caernarvon (m)	Peak surge Barataria (m)
S1	960	38.9	5.7	T1	3.5	2.3
S2	900	40.4	5.7	T1	6.8	4.1
S3	960	32.8	3.1	T1	4.2	2.3
S4	900	40.4	5.7	T2	4.5	4.3

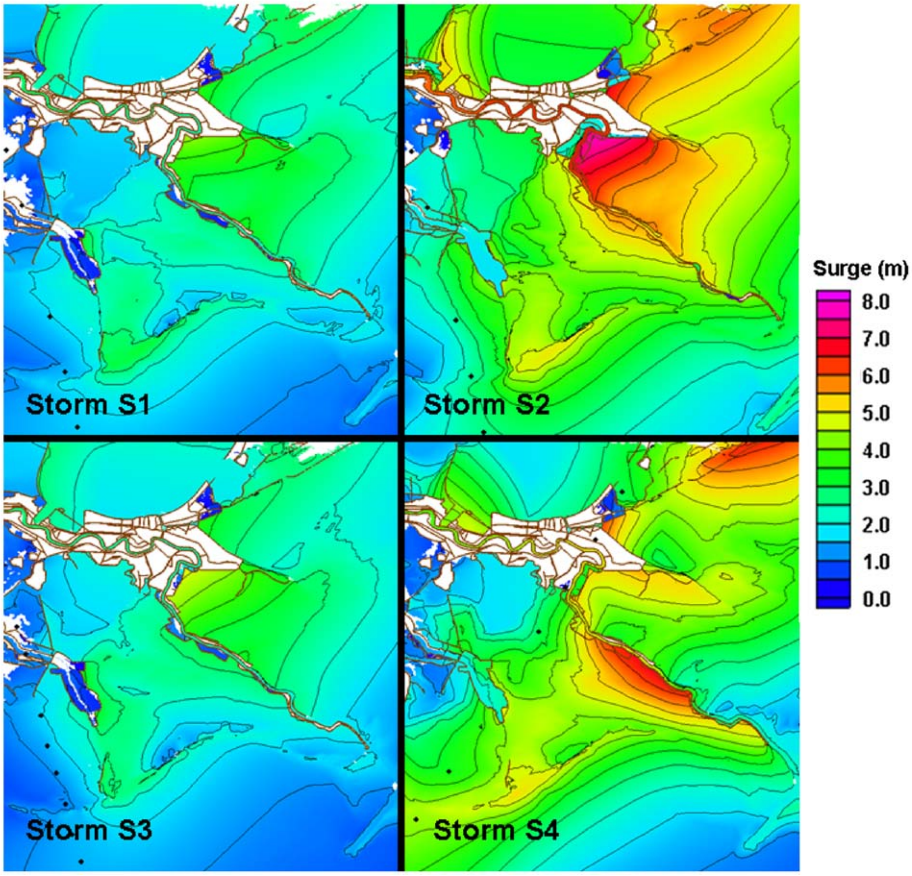

Fig. 5. Base condition peak surge for sensitivity storm suite.

responses across these two wetlands is the surrounding bathymetry and topography. At Caernarvon the surge is heavily influenced by the presence of the Mississippi River levees that border the marsh on the west and south. The levees hold the water over the marsh and if the wind forcing is long enough in duration, water is pushed into the Caernarvon marsh and is not able to propagate out.

For a faster moving storm, the effect is diminished as seen by the lower surge level at the back of the profile for Storm S1 versus the similar but slower moving Storm S3. The peak water level near the back levee is approximately 0.7 m higher for the slower moving storm. The results in Fig. 6 also indicate that the decrease in surge over Barataria would likely have been greater in this area if the extent of wetlands was greater. The surge decreases over the wetlands on the seaward and landward side of Little Lake but generally increases over the lake itself. The surge attenuation rate across the seaward wetland ranged from 1 m per 25 km (Storm S3) to 1 m per 10 km (Storm S2); the range for the landward wetland was 1 m per 11 km (Storms S1 and S2) to 1 m per 6 km (Storm S4). Note that these attenuation rates are consistent with those calculated from measurements of Hurricane Rita surge in western Louisiana. The variability of the surge response over similar wetlands for the same storm is further illustrated by the different surge attenuation rates for the seaward and landward wetlands in the Barataria basin for Storm S4. For this storm, these two wetland areas in close proximity have attenuation rates of 1 m per 14 km and 1 m per 6 km, additional evidence that constant attenuation rate assumptions are not supportable.

The value of wetlands in attenuating surge is further illustrated by examining the difference in surge for the base and future conditions to isolate various forcing parameters, which will be referred to as a marginal attenuation rate. For this analysis, the focus is on the wetland areas that changed between the base and estimated future conditions. Fig. 7 plots the difference in the peak surge between the future and base conditions for Caernarvon with reaches of wetland degradation and restoration identified. Results in Fig. 7 indicate that the loss of wetlands does increase surge in the Caernarvon area for the storms simulated. So, while the surge increases as it propagates over the wetland (as seen in Fig. 6), without the fronting wetland the surge increases by an even

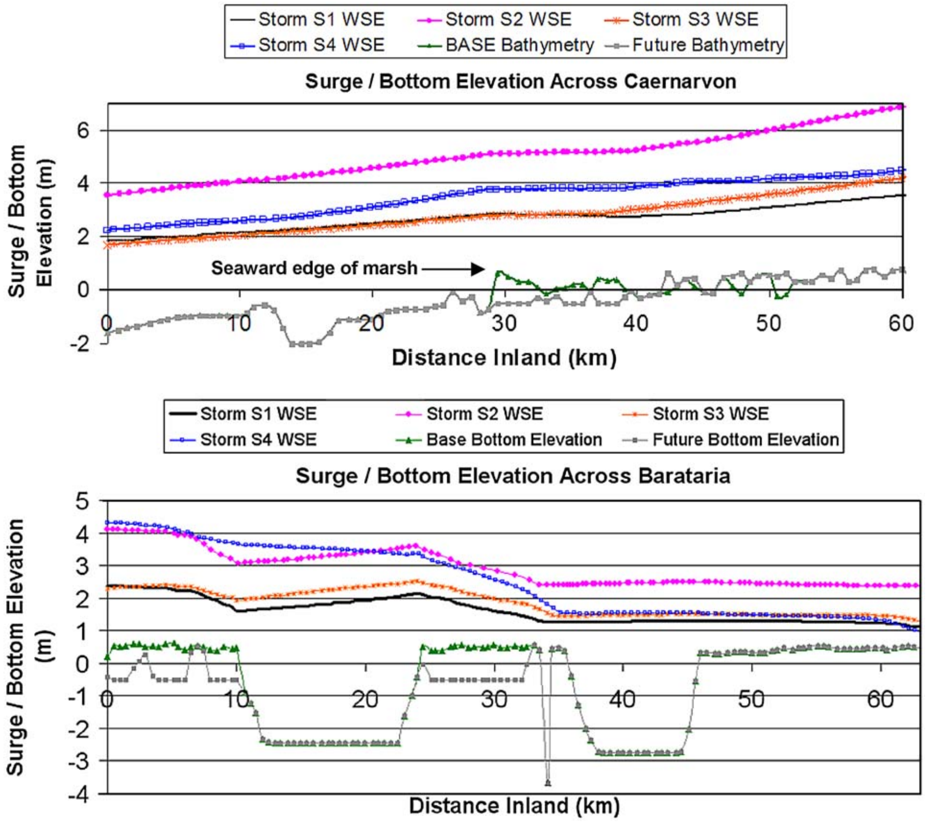

Fig. 6. Surge across Caernarvon and Barataria profiles for the base condition.

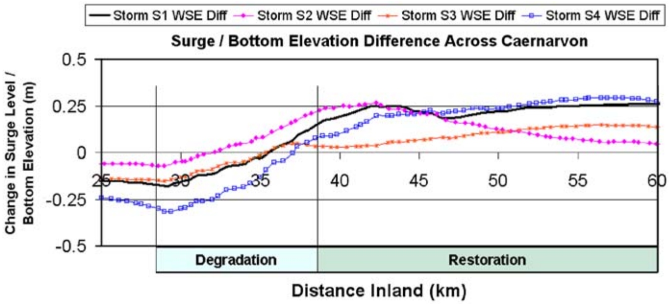

Fig. 7. Peak surge difference between the future and base conditions (future–base) in Caernarvon.

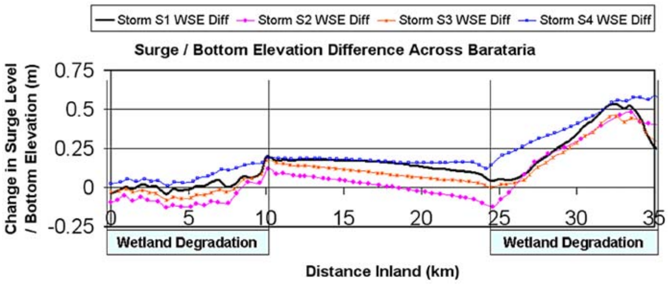

Fig. 8. Peak surge difference between the future and base conditions (future–base) in Barataria.

greater amount. The greatest increase in surge over Caernarvon due to the lost wetlands is approximately 0.4 m for storm S4. The 0.4 m increase over 10 km of wetland loss indicates a marginal surge attenuation rate of approximately 1 m per 25 km of marsh. This storm is the most sensitive to the loss of wetlands, which is expected since the track for this storm produces winds that push water into the Caernarvon marsh for the shortest duration due to the angle at which the storm approaches the coast. The storm that is least sensitive to the loss of wetlands is S3, the slow moving storm. For storm S3, winds blow water into Caernarvon for the longest period of time and the computed increase in surge for this storm as a result of the wetland loss is less than 0.2 m. The wetlands and associated friction only slow the surge propagation and if the winds blow strong enough for a long enough time period, the value of a wetland for coastal protection is minimized. Storms S1 and S2 both have an increase in surge across the degraded wetland of 0.3 m, resulting in a marginal surge attenuation rate of 1 m per 33 km of marsh.

Note also from Fig. 4 that the Caernarvon marsh future condition includes both loss of bottom elevation and land building. The degraded marsh in front of the restored area allows more water into the restored area, where the surge propagation is slowed resulting in further increased surge over the restored wetland relative to the base condition. The restored wetland does not result in reduced surges at Caernarvon as the bordering levees trap the water propagating into this area. The difference in surge at the back levee increases for all storms. The increase for S2 is small as this storm significantly overtops the back levee and thus the levee height influences the peak water levels for that storm.

Fig. 8 plots the difference in peak surge between the future and base conditions in Barataria with reaches of wetland degradation indicated. For all storms, the loss of the wetlands seaward of Little Lake resulted in approximately a 0.2 m increase in surge over 10 km, suggesting a marginal surge attenuation rate of 1 m per 50 km of wetland. The surge response in this area is also influenced by the presence of fronting barrier islands. The surge response is more sensitive to the loss of the wetland landward of Little Lake. The surge increases approximately 0.5 m over 9 km of degraded wetlands for each storm, indicating that the wetlands provided an increased attenuation rate of about 1 m per 18 km of wetland.

To better understand how wetlands may change the level of protection, a stochastic analysis was also performed. A set of 304 synthetic storms was simulated for the Louisiana coast for both the base and future conditions. A joint probability method analysis was performed to estimate the 100- and 1000-yr surge level across the Caernarvon and Barataria wetland profiles (Interagency Performance Evaluation Task Force, 2007). The results for Caernarvon and Barataria are plotted in Figs. 9 and 10, respectively. Fig. 9 shows that the loss of Caernarvon

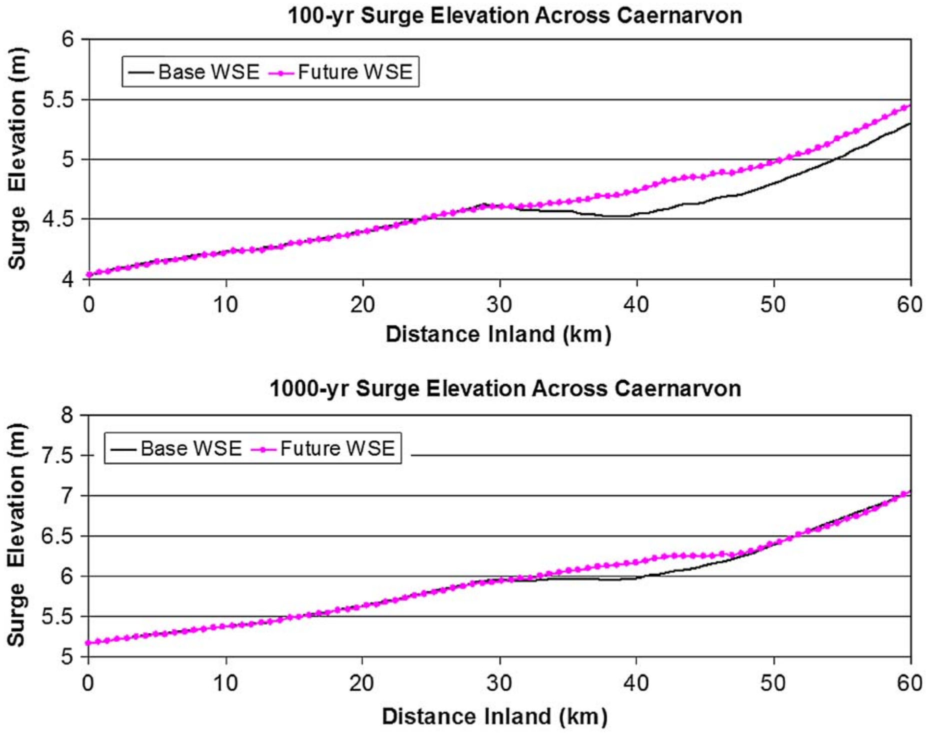

Fig. 9. The 100- and 1000-yr surge level across Caernarvon for the base and future condition.

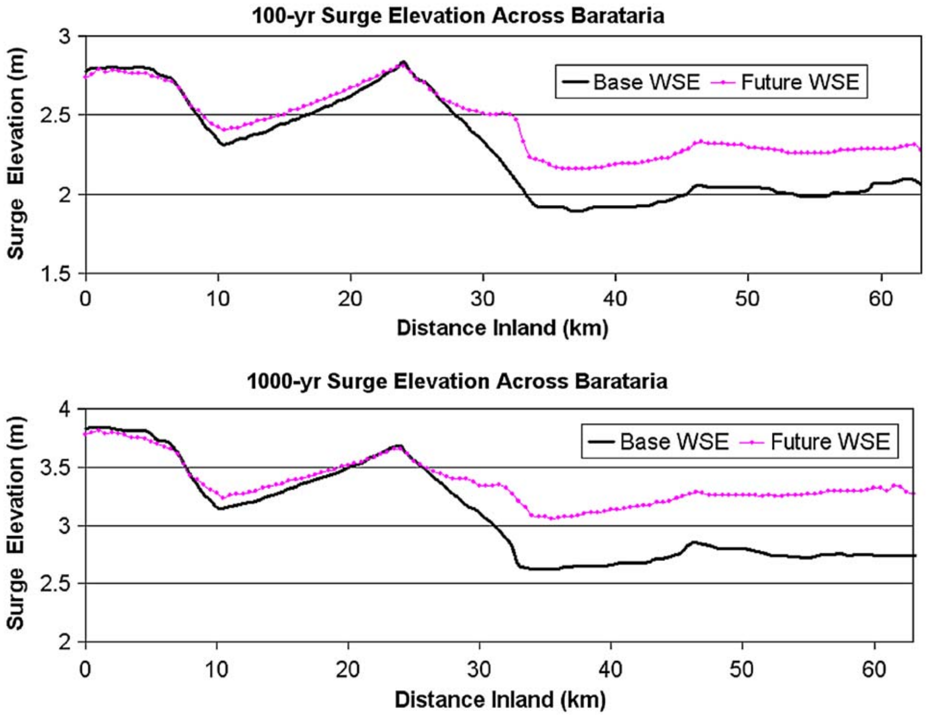

Fig. 10. The 100- and 1000-yr surge level across Barataria for the base and future condition.

wetlands increases the 100-yr surge elevation by less than 3%. The calculated increase in the 100-yr surge for the future condition at the protection system is only about 15 cm. The future condition also included an area of restored wetlands that may have slowed surge propagation relative to the base condition here, thus countering the impact of wetland loss and reducing the increase in water level at the back levees. The change in wetland condition results in no change in the 1000-yr water surface elevation at the protection system. The 1000-yr water level overtops the back levee and thus the water level at the protection system is controlled by the levee height. The future condition does have a slightly higher water level over portions of the marsh, but the large surges overwhelm the marsh and the protection system in this area regardless of the condition of the wetlands. Isolating the influence of the seaward portion of marsh that degraded (from cross-shore distance 29 to 39 km), results indicate that the wetland surge attenuation rate is approximately 1 m per 50 km at both the 100- and 1000-yr levels.

Fig. 10 plots the surge attenuation across Barataria for the 100- and 1000-yr water levels. For both the base and the future conditions, the surge is attenuated as it propagates inland. The 100-yr surge elevation is reduced by about 0.8 m across 60 km of wetlands and open water for the base condition and is reduced about 0.5 m for the same 60 km for the future degraded condition. The difference of 0.3 m is about a 15% reduction in the 100-yr water level. The wetlands reduce the 1000-yr surge levels by about 20%. The 1000-yr surge elevation is attenuated by about 1 m across 60 km of wetlands and open water for the base condition. With the wetlands degraded, the surge reduction is only 0.5 m across the same 60 km. Isolating the influence of the wetland landward of Little Lake (which is removed from the impact of the barrier islands), a surge reduction rate of approximately 1 m per 30 km is computed for the 100-yr level and a rate of approximately 1 m per 20 km for the 1000-yr level. The greater attenuation rate estimated for the more powerful storms may seem somewhat counter intuitive. However, this is attributed to the transient nature of the forcing in this wetland area. Retarding the steeper surge front associated with stronger storms reduces the water volume pushed inland relative to weaker storms. In Caernarvon, the result is different because the surge along this portion of the coast is attributable to wind forcing over greater durations and the surrounding levees preclude the water from continuing to move inland.

6. Conclusion

The purpose of this study is to investigate the role of wetlands for coastal protection. The potential of wetlands to reduce storm surge has typically been expressed by rules of thumb based on heterogeneous observations. The empirical data on which these rules are based have a high degree of scatter because of complex and transient governing physical processes, which are dependent on many details including storm intensity, track, forward speed, and surrounding local bathymetry and topography. A validated, integrated modeling system that simulates the relevant processes was applied to better understand how wetlands influence storm surge. Analyses of model results indicate that the surge attenuation rates estimated by the numerical modeling system are consistent with observations. The range of surge attenuation rates from measured data is 1 m per 60 km to 1 m per 4 km; the range from model results is 1 m per 50 km to 1 m per 6 km. Both model results and observed data suggest that wetlands do have the potential to reduce surges but that it is dependent on the landscape (bathymetry, structures, and wetland characteristics) and storm characteristics (size, speed, track, and intensity). The effectiveness of wetlands at attenuating surge is primarily dependent on the surrounding coastal landscape and the strength and duration of the relevant forcing. The forcing duration is primarily governed by the forward speed of the storm and the track on which it approaches the coast. The combination of the geometry of the coastal landscape and how a storm approaches that landscape determines the duration over which water is pushed inland.

The influence of wetlands on surges was also investigated stochastically to better quantify how they may impact levels of protection. The 100- and 1000-yr surges were computed for profiles across both Caernarvon and Barataria. The loss of wetlands increased the 100-yr water surface elevation by about 0.15 m in Caernarvon and 0.3 m in Barataria. The 1000-yr water surface elevation was not affected by the loss of wetlands in Caernarvon as the system was overwhelmed with surge (over 7 m at the protection system). In Barataria, the loss of wetlands increased the 1000-yr water surface elevation by about 0.5 to 0.6 m.

Wetlands do play a role in coastal protection. The effectiveness of the wetlands is variable along the coast and dependent on key storm parameters. Therefore, the application of a constant attenuation rate is misleading and not appropriate. For a given storm, depending on forward speed, track, and intensity, a wetland may not attenuate surge at all. In general, however, wetlands do attenuate surge and they should be considered when developing a comprehensive plan for coastal protection.

Numerical models that simulate the relevant physical processes can provide valuable information on how to best integrate wetlands for coastal protection. However, while the numerical model applied for this study has displayed skill in estimating surges over wetlands, the formulations are missing key processes and improvements are necessary. Additional processes that should be considered include changes to the wetlands (such as stripping of vegetation cover and erosion of land masses) that occur during passage of a storm; improved frictional formulations that explicitly accounts for both bottom friction and form drag; wave set up in the presence of vegetation; consideration of three-dimensional effects; consideration of sub-grid scale channels through marshes; and changes in the structure of the hurricane itself due to the landfall infilling phenomenon that may be influenced by the presence of wetlands.

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