8.2 INCLUDING SPATIALLY-VARYING BOTTOM FRICTION WITHIN THE SLOSH MODEL

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1. INTRODUCTION

The Sea, Lake, and Overland Surges from Hurricanes (SLOSH) (Jelesnianski et al. 1992) is a numerical storm surge model developed and used by the National Weather Service (NWS). It is an extremely computationally efficient, 2-D explicit, finite-difference model, formulated on a semi-staggered Arakawa B-grid (Arakawa 1977). The SLOSH model transport equations were derived by Platzman (1963), in which the dissipation is determined solely by an eddy viscosity coefficient. The horizontal transport equations are solved through the application of the Navier-Stokes momentum equations for incompressible and turbulent flow, and are integrated over the entire depth of the water column. At every time step, the horizontal transports are solved from the pressure, Coriolis, and frictional forces to generate an updated water level at every grid point (Forbes et al. 2014). Narrow sub-grid scale features, such as canals and rivers, are incorporated via simple 1-D hydraulic procedures.

SLOSH includes a wetting-and-drying algorithm to predict inland inundation. Conceptually, if water fills a cell, it can fill adjoining cells, however the algorithm also incorporates the need to overtop barriers such as levees, train tracks, and elevated roads. A constant bottom slip coefficient instead of a spatially varying Manning coefficient was used to calculate the bottom friction term (Platzman 1963; Jelesnianski 1967).

A parametric wind model developed by Jelesnianski and Taylor (1973) is embedded in the SLOSH model. It requires parameters of the storm track (latitude and longitude of the center of the storm), radius of maximum winds, and the delta pressure between the environmental and the central pressures (pressure drop) of the storm. Alternatively, a gridded wind and pressure field can be used as the atmospheric forcing.

Previous studies have shown the SLOSH model to be effective in supporting the National Hurricane Center's (NHC) storm surge watches and warnings. It is used by the NWS primarily in three ways. First, via hypothetical simulations to estimate potential storm surge hazards for evacuation planning. Second, via probabilistic simulations within either the Probabilistic tropical cyclone storm Surge model (P-Surge), or the Probabilistic Extra-Tropical Storm Surge model (P-ETSS) to estimate the real-time hazard. Third, via historical simulations for post storm response-and-recovery and model validation-and-analysis.

While SLOSH was originally developed in the 1980s and 1990s, there have been more recent developments. In 2011, astronomical tides were incorporated to account for nonlinear interactions between surge and tide (Haase et al. 2011). In 2015, the ability to nest a narrow, fine-resolution grid within a broader coarser grid was added (Liu et al. 2015). This enabled the model to incorporate remote changes to the water level into the local water level simulations. In 2020, a parallel version, using domain decomposition and the Message Passing Interface (MPI), was developed to help address the computational time requirements of broader-and-finer basins (Taylor and Liu, 2020).

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Also, in 2020, a wave-surge coupling system using a 2nd-generation wave model was under development (Yang et al. 2020).

While these improvements addressed some of the SLOSH model's weaknesses, it still has other challenges that need to be addressed. One such challenge is over-forecasting the extent of inundation by using a constant bottom friction coefficient and thereby neglecting the effect of spatially varying land cover. Physically different land cover types such as forest and bare land have different effects on wind stress and bottom friction. As a result, the inundation process in a vegetated area should differ from the process in a bare land area.

Numerous studies have investigated the effects of land cover type on attenuating storm surge and inundation areas. (Resio and Westerink 2008; Mattocks and Forbes 2008; Zhang et al. 2012; Sheng et al. 2012; Liu et al. 2013; Sheng and Zou 2017; Rodriguez et al. 2017). All of the studies show that forests, especially mangroves, significantly reduce the inundation area and thereby mitigate the impacts of storm surge on coastal communities. One popular and efficient way to incorporate the impacts of land cover into storm surge models is via a spatially varying Manning coefficient based on the land cover type (Zhang et al. 2012; Liu et al. 2013; Rodriguez et al. 2017). Particularly, Zhang et al. (2012) and Liu et al. (2013) used the spatially varying Manning coefficient in the Coastal and Estuarine Storm Tide (CEST) model (Zhang et al. 2008) to incorporate the effects of different land cover on storm surges and successfully replicated the magnitude and extent of overland flooding caused by Hurricane Wilma in 2005.

The purpose of this paper is to describe the development of a numerical method within SLOSH to incorporate the effects of different land cover types on the storm surge and inundation simulation. This includes (1) introducing spatially varying Manning coefficient values for land grid cells based on land-cover type into the SLOSH basin, and (2) developing a method to convert the Manning coefficient values to the slip coefficient used within SLOSH which properly accounts for the effect of land cover. For step 1, we use a similar method of parameterizing the Manning coefficient based on land cover type as was done in Zhang et al. (2012) and Liu et al. (2013). To verify the results, we run SLOSH with and without the effect of land cover by using two historical hurricanes (Hurricane Rita, 2005 and Hurricane Ike, 2008). Observations were used to verify the SLOSH numerical simulations.

The rest of the manuscript is organized as follows: Section 2 describes the method used to incorporate the effects of different land-cover types within SLOSH. Section 3 describes the model settings and experiments. The model results are presented in Section 4. Finally, a discussion and summary are provided in Section 5.

2. METHODOLOGY

2.1 *Calculation of Manning coefficient values based on land cover type*

One popular method to parameterize the bottom coefficient is calculated by:

$$C_b = \frac{gn^2}{H^{\frac{1}{3}}}$$

where C_b is the bottom coefficient, g is the gravitational constant, n is the Manning coefficient, and H is the total water depth. This method requires that the Manning coefficient be provided. Typically, Manning coefficients are derived from the land cover types within the National Land Cover Dataset (NLCD) with a spatial resolution of 30 m (Homer et al. 2004). Manning coefficient values for each land cover class used in this study are shown in Table 1. Since the pixel size of the NLCD dataset is typically smaller than a SLOSH grid cell, an average of the Manning coefficients (n_a) is calculated using all pixels within the cell. There are some grid cells where there is no average value, either because the NLCD didn't cover the area or the cell is covered by water. In those cases, a default Manning coefficient is assigned. Thus, the Manning coefficient at any given SLOSH model grid cell is calculated by:

$$n_a = \frac{\sum_{i=1}^{N} n_i \alpha + n_{0\beta}}{N\alpha + \beta}$$

where n_i are Manning coefficient values of a NLCD pixel within a model grid cell, α is the area of a NLCD pixel, N is the total number of NLCD pixels within a model cell, n_0=0.02 is the default Manning coefficient, and β is the grid cell area not covered by NLCD pixels. Only grid cells which cover both land and water areas involve non-zero β values.

Table 1. Manning coefficients for various categories of land cover

NLCD Class Number	NLCD Class Name	Manning Coefficient
11	Open Water	0.02
12	Perennial Ice/Snow	0.01
21	Developed Open Space	0.02
22	Developed Low Intensity	0.05
23	Developed Medium Intensity	0.1
24	Developed High Intensity	0.13
31	Barren Land (Rock/Sand/Clay)	0.09
32	Unconsolidated Shore	0.04
41	Deciduous Forest	0.1
42	Evergreen Forest	0.11
43	Mixed Forest	0.1
51	Dwarf Scrub	0.04
52	Shrub/Scrub	0.05
71	Grassland/Herbaceous	0.034
72	Sedge/Herbaceous	0.03
73	Lichens	0.027
74	Moss	0.025
81	Pasture/Hay	0.033
82	Cultivated Crops	0.037
90	Woody Wetlands	0.14
91	Palustrine Forested Wetland	0.1
92	Palustrine Scrub/Shrub Wetland	0.048
93	Estuarine Forested Wetland	0.1
94	Estuarine Scrub/Shrub Wetland	0.048
95	Emergent Herbaceous Wetlands	0.045
96	Palustrine Emergent Wetland (Persistent)	0.045
97	Estuarine Emergent Wetland	0.045
98	Palustrine Aquatic Bed	0.015
99	Estuarine Aquatic Bed	0.015

2.2 *Conversion of Manning coefficient values to slip coefficient*

The depth integrated governing equations of SLOSH are

$$\frac{\partial h}{\partial t} = -\frac{\partial U}{\partial x} - \frac{\partial V}{\partial y}$$

$$\frac{\partial U}{\partial t} = -g(D+h)\left[B_r\frac{\partial (h-h_0)}{\partial x} - B_i\frac{\partial (h-h_0)}{\partial y}\right] + f(A_rV + A_iU) + C_r x_T - C_i y_T$$

$$\frac{\partial V}{\partial t} = -g(D+h)\left[B_r\frac{\partial (h-h_0)}{\partial y} + B_i\frac{\partial (h-h_0)}{\partial x}\right] + f(A_rU - A_iV) + C_r y_T + C_i x_T$$

where U and V are the components of transport, g is the gravitational constant, D is the depth of quiescent water relative to datum, h is the height of water above datum, h_0 is the hydrostatic water height, f is the Coriolis parameter, x_T and y_T are components of surface stress, and A_r, A_i, B_r, B_i, C_r, and C_i are bottom stress terms. These equations were developed by Platzman (1963) and modified with a bottom slip coefficient by Jelesnianski (1967). The equations are different from those used in many other models which use bottom stress derived from Manning coefficients.

As SLOSH uses a slip coefficient instead of Manning coefficients to calculate the bottom friction term, the Manning coefficient created in section 2.1 cannot be directly used. Instead, a formula was needed to convert a Manning coefficient to a slip coefficient. Based on previous experiments, SLOSH was able to generate fairly good inundation maps when compared to CEST based results if it used a slip coefficient value between 0.1 and 0.25 for overland cells in various newly developed SLOSH basins. So, a reasonable formula was to set the slip coefficient (C7) at any given SLOSH model grid cell as follows:

$$C7 = \begin{cases} 0.006 & if\ d > 0 \\ 0.1 & if\ d \le 0\ and\ n_a \le 0.1 \\ f(n_a) & if\ d \le 0\ and\ 0.1 < n_a \le 0.25 \\ 0.25 & if\ d \le 0\ and\ n_a > 0.25 \end{cases}$$

where d is the water depth ($d > 0$ for a water cell and d ≤ 0 for a land cell), n_a is the average Manning coefficient in a grid cell, and $f(n_a)$ is a function of n_a. Currently $f(n_a) = n_a$ is performing well in the test cases.

3. MODEL SETTINGS AND EXPERIMENTS

3.1 *Model Settings*

The newly developed super Texas basin (TX3) is used in this study to explore the effects of land cover on storm surge and overland inundation. TX3 is shown in Figure 1 with its grid centered on Galveston Bay and extending out to the border of Mexico in the west, to the deep-water area of the Gulf of Mexico in the south, and to New Orleans, LA in the east. It is well suited to handling hurricanes making landfall in or near the Galveston Bay region. The grid resolution is around 100-200 m in the Galveston Bay area and 1-2 km in the deep ocean.

The calculated Manning coefficients based on the land cover type, as described in Section 2.1, are also shown in Figure 1. It shows that the overland cells with large Manning coefficients are located between the northeast of Galveston Bay, Texas, and Lake Charles, LA, which means the Manning formulation should help dissipate the storm surge heights and reduce inundation in those areas.

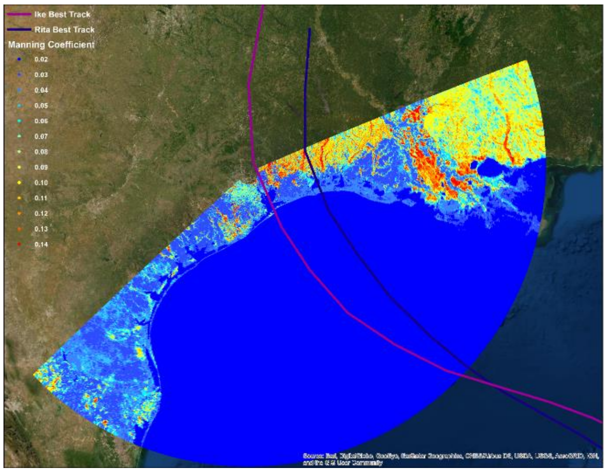

Figure 1. Super Texas SLOSH basin, calculated Manning coefficient based on National Land Cover Dataset (NLCD), and the best tracks of hurricane Rita in 2005 and hurricane Ike in 2008 overlaid on the basin.

3.2 Experiments

Simulations of inundation induced by Hurricane Rita in 2005 and Ike in 2008 were used to verify the SLOSH model results and examine the effects of including spatially varying land cover within the calculations. Both hurricanes made landfall around the center of TX3 and caused significant storm surge and inundation, which made them excellent test cases for this study. The best tracks for both Hurricane Rita and Ike are shown in Figure 1. Hurricane Rita made landfall across western Cameron Parish just east of the Texas and Louisiana border on 24 September 2005 as a category 3 Hurricane. It produced storm surge values of 12 to 18 feet across most of Cameron parish, and 10 to 12 feet across most of Vermilion parish, devastating both areas. Storm surge values of 8 to 10 feet across eastern Jefferson and Orange counties in Southeast Texas caused considerable damage to Sabine Pass and Bridge City (Knabb et al. 2006). Hurricane Ike made landfall near Galveston, Texas on 13 September 2008 as a category 2 Hurricane. It produced a damaging, destructive, and deadly storm surge across the upper Texas and southwest Louisiana coasts.

In order to verify the results and examine the effects of land cover on storm surge, two simulations of Hurricane Rita and two of Hurricane Ike were conducted in TX3. The first simulation for each storm used a constant slip coefficient (0.006) for all grid cells (SLOSH W/O Manning). The second simulation used the spatially varying slip coefficient for land cells based on the methodology introduced in Section 2 (SLOSH W/ Manning) and a constant slip coefficient for water cells.

4. RESULTS

4.1 *Hurricane Rita*

The peak storm surge heights computed by SLOSH for Hurricane Rita are shown in Figure 2. Figure 2a shows the result of SLOSH using a constant slip coefficient for the entire grid (SLOSH W/O Manning) and Figure 2b shows the result of SLOSH incorporating the effects of land cover (SLOSH W/ Manning). Together they show that storm surge inundates more inland areas when SLOSH uses a constant slip coefficient (SLOSH W/O Manning) in the Lake Charles region. In other words, it indicates that incorporating the effects of land cover reduces the extent of inundation there.

Figure 2a also shows two peak storm surge areas: one along the open coastline and one in the inland inundation area. That implies there is insufficient dissipation of overland surge in the SLOSH W/O Manning result. In contrast, the simulation that incorporated the effects of land cover has one peak surge center (along the open coastline), which implies it reduced the storm surge heights that traveled overland (Figure 2b). In general, the overall flooding pattern from the SLOSH W/ Manning simulation appears to be more realistic.

It is worth noting that larger bottom friction, in the case where SLOSH accounts for land cover

(SLOSH W/ Manning), helped build up more storm surge along the open coastline. Based on the estimate from NHC's Tropical Cyclone Report Hurricane Rita (Knabb et al. 2006), 12 to 18 feet of storm surge was experienced across most of Cameron parish, which is in good agreement with the SLOSH W/ Manning simulation.

To delve deeper into how it performed, we compared observed water level time series from National Oceanic and Atmospheric Administration (NOAA) tide gauges at Rainbow Bridge (8770520) and Port Arthur (8770475) with both simulated results for Hurricane Rita in 2005 (Figure 3). We did not expect much difference between the two simulations at the gauges as there is no change to the slip coefficient in water cells. However, the results show a significant improvement at both NOAA tide gauges. This is most likely due to both tide gauges being located inside either a canal or river channel rather than along the open coastline (Figure 2). Figure 1 shows that there are large Manning coefficient values in the areas surrounding both tide gauges. The large bottom friction in the surrounding areas reduced the computed storm surge height at both tide gauges.

The U.S. Geological Survey (USGS) starting in roughly 2005, but more consistently since 2008, deploys storm tide monitoring sensors overland along the potential hurricane impacted route. As a group, these typically temporary sensors measure the timing, areal extent, and magnitude of coastal flooding generated by hurricanes. One group of these sensors was deployed in Hurricane Rita and recorded water level time series for locations which are typically dry (Figure 4). The comparison of the

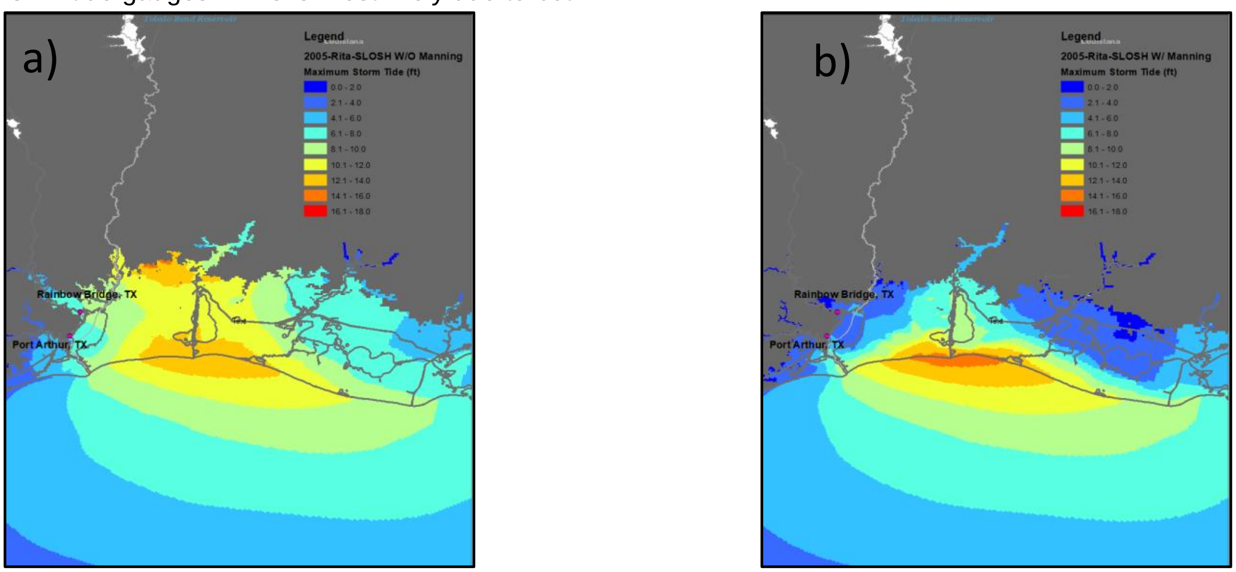

Figure 2. The peak storm surge heights during Hurricane Rita simulated by SLOSH without Manning (a) and with Manning (b).

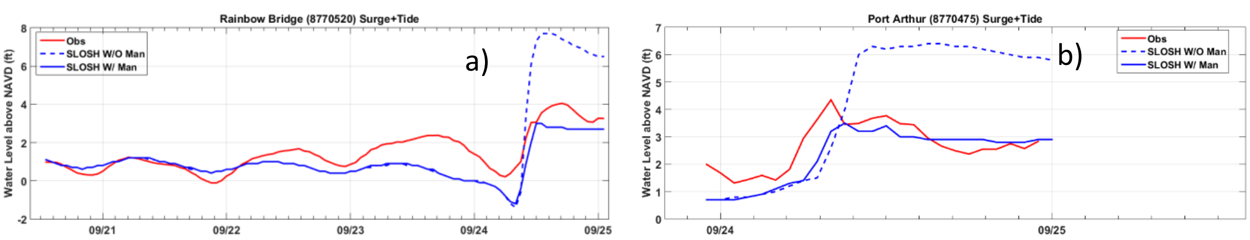

Figure 3. Time series of water level at a) Rainbow Bridge (8770520) and b) Port Arthur (8770475). The red line is the observation, the dashed blue line is the SLOSH W/O Manning, and the solid blue line is the SLOSH W/ Manning result.

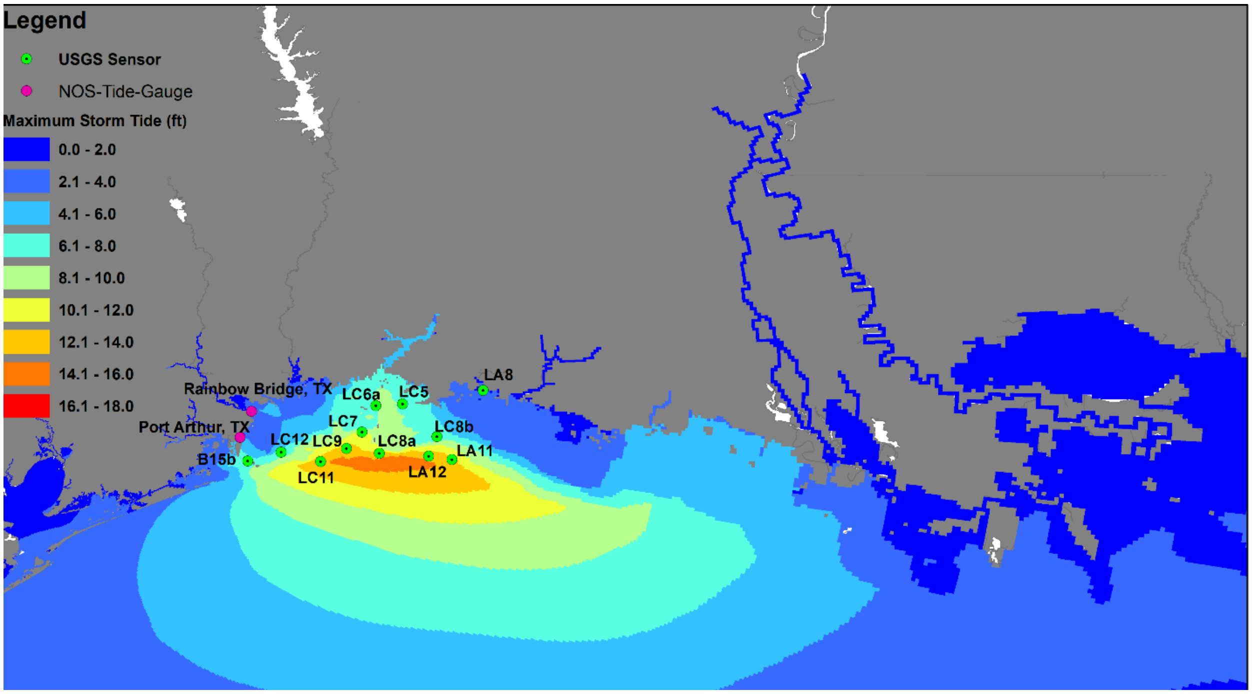

Figure 4. Locations of USGS deployed sensors during Hurricane Rita

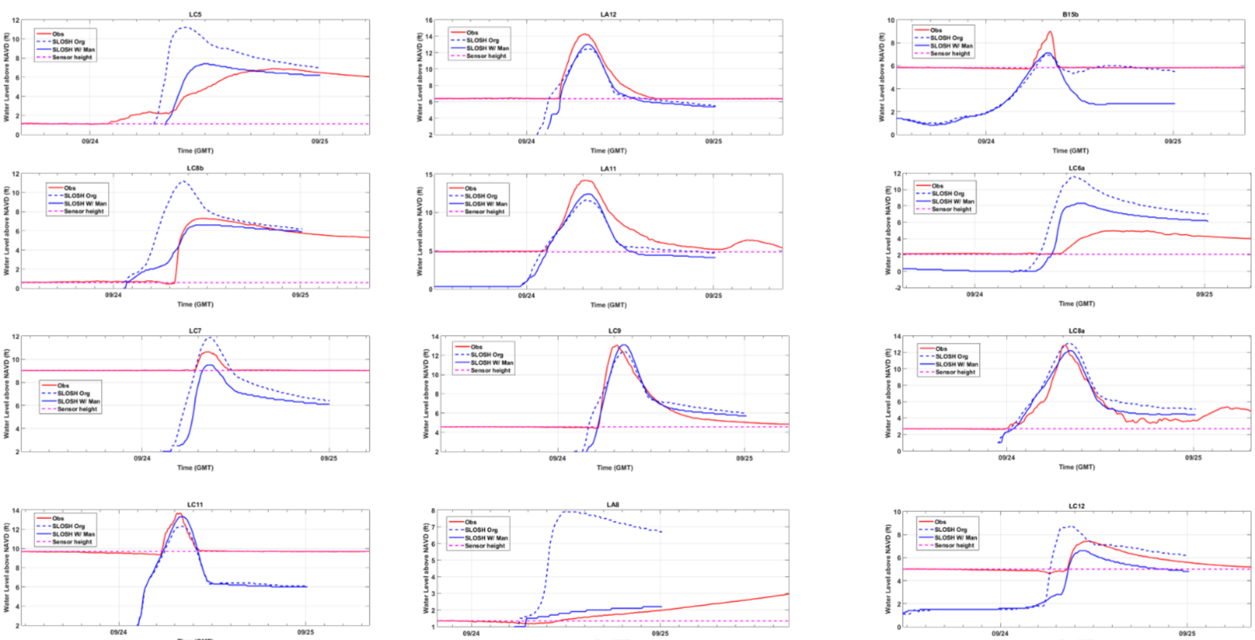

Figure 5. Time series of water level at USGS sensors. From top left to right, and top to bottom, the plots represent results from station LC5, LA12, B15b, LC8b, LA11, LC6a, LC7, LC9, LC8a, LC11, LA8, and LC12. The red line is the observation, the dashed blue line is the SLOSH W/O Manning, and the solid blue line is the SLOSH W/ Manning result.

observed water level time series with the computed water level time series from both simulations is shown in Figure 5. Overall, it indicates that incorporating the effects of land cover into SLOSH improved the storm surge simulations at those overland locations. It is worth noting that it significantly improves the storm surge simulation at 4 stations named LC6a, LC5, LC8b, and LA8. Just as with the two NOAA tidal gauges, the high Manning coefficient values (Figure 1) can be seen in those sensors' surrounding areas. This indicates that in order to simulate reasonable storm surge height it is essential that the model incorporates the large bottom friction in those areas.

In the US, High Water Marks (HWM) are gathered during post storm surveys for significant named storms. The USGS has placed a large number of them on its flood event viewer (https://stn.wim.usgs.gov). The available HWM for Hurricane Rita are shown in Figure 6a. The computed peak surges versus observed ones at the HWM locations show the impact of land cover in reducing the over-forecasted area (Figure 6b). In short, land cover plays a great role in attenuating overland storm surge. Root Mean Square Error (RMSE) of computed peak surge heights versus observed decreases from 2.6 ft to 2.4 ft when the effects of land cover are incorporated into the SLOSH model.

4.2 *Hurricane Ike*

Figure 7 shows the computed peak storm surge heights for Hurricane Ike with SLOSH using a constant overland slip coefficient (SLOSH W/O Manning) (Figure 7a) and a spatially varying overland slip coefficient incorporating the effects of land cover (SLOSH W/ Manning) (Figure 7b). The maximum surge heights are around 20 ft above NAVD 88 from both SLOSH runs, which is in good

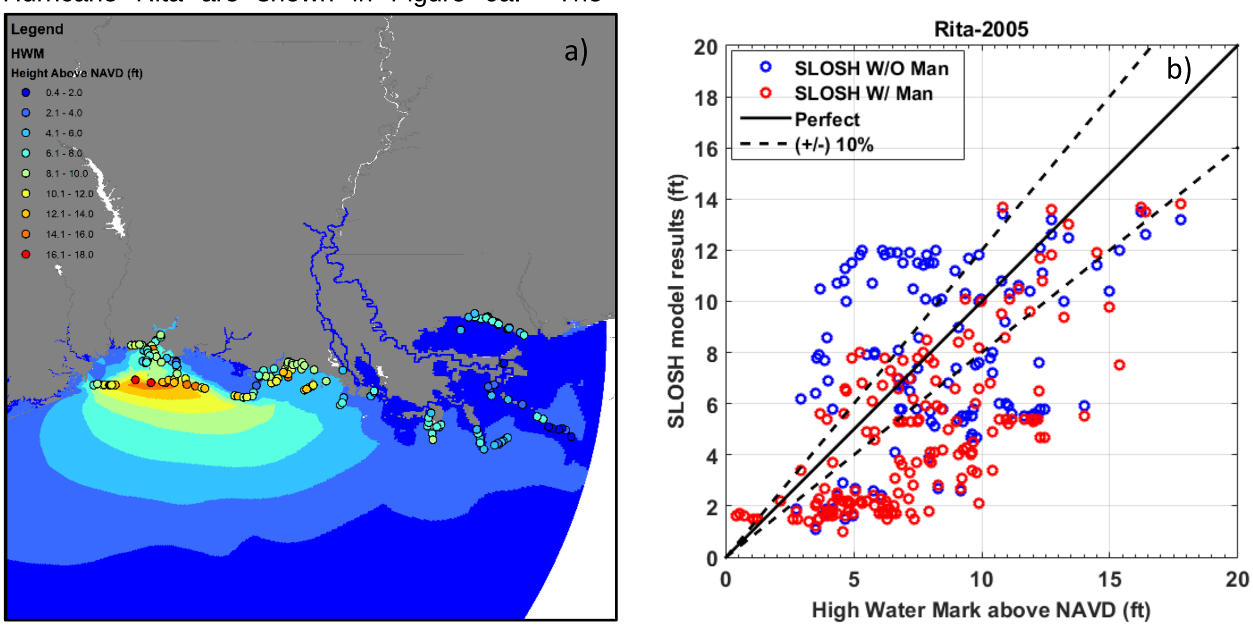

Figure 6. a) Locations of High Water Marks, and **b)** scatter plot of observed HWM versus SLOSH computed results.

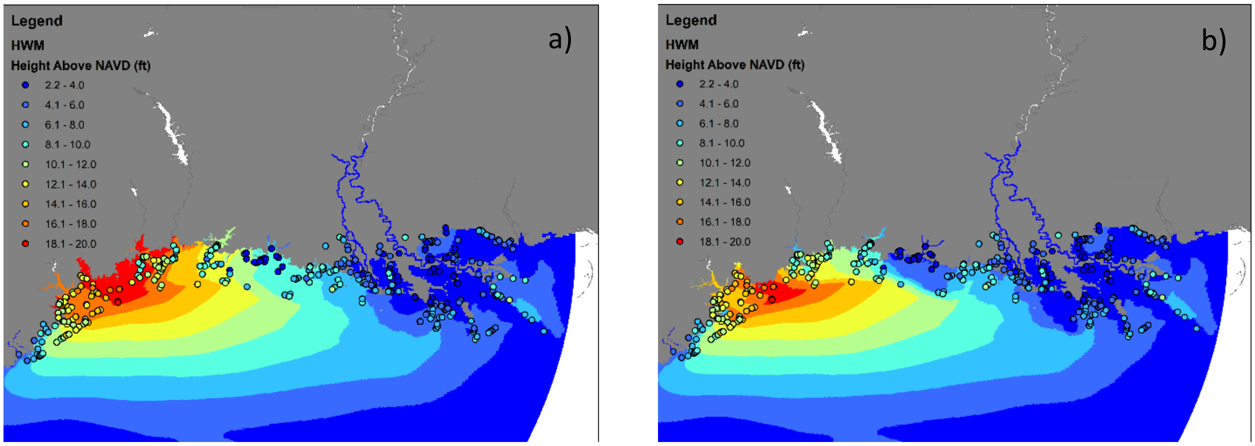

Figure 7. The peak storm surge heights during Hurricane Ike simulated by SLOSH W/O Manning (a) and SLOSH W/ Manning (b).

agreement with the 15 – 20 ft estimate from the NHC's Tropical Cyclone Report Hurricane Ike (Berg, 2009). However, the inundation extents and maximum storm surge distribution show a large difference between these results. The inundation extents from SLOSH W/O Manning are much larger than those from SLOSH W/ Manning results. Also, the maximum storm surge heights from SLOSH W/O Manning are relatively evenly distributed from the coastline to the inland inundation line without much dissipation. In contrast, the maximum storm surge heights from SLOSH W/ Manning are limited at the coastline and to the east of Galveston Bay, which is in better agreement with the Tropical Cyclone Report for Hurricane Ike. The description of maximum storm surge in the report is: "The highest storm surge occurred on the Bolivar Peninsula and in parts of Chambers County, Texas (including the east side of Galveston Bay), roughly between the Galveston Bay entrance and just northeast of High Island." (Berg 2009) The overland surge dissipation is much more pronounced in the SLOSH W/ manning simulation.

Figure 8 shows the comparison of computed peak storm surge heights versus observed ones from the USGS HWM sensors (see Figure 7 for sensor locations). Incorporating the effects of land cover into the SLOSH model significantly reduces the variability of computed versus observed peak surge heights (Figure 8). It also shows that dissipation of overland surge caused by incorporating the effects of land cover reduces over-forecasting at overland cells. In this case, incorporating the effects of land cover reduced the RMSE of computed peak surge heights versus observed ones significantly from 3.6 to 2.2 ft.

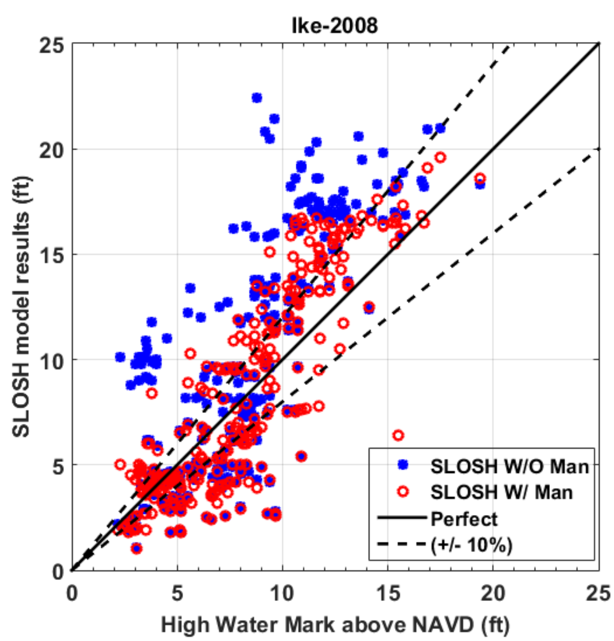

Figure 8. Scatter plot of observed HWM versus SLOSH computed results.

The time series comparisons at both NOAA tide gauges (the first row) and overland USGS sensors (the remaining three rows) are shown in Figure 9 (see Figure 10 for tide gauge and sensor locations). It shows noticeable improvements at most NOAA tide gauges and USGS sensors.

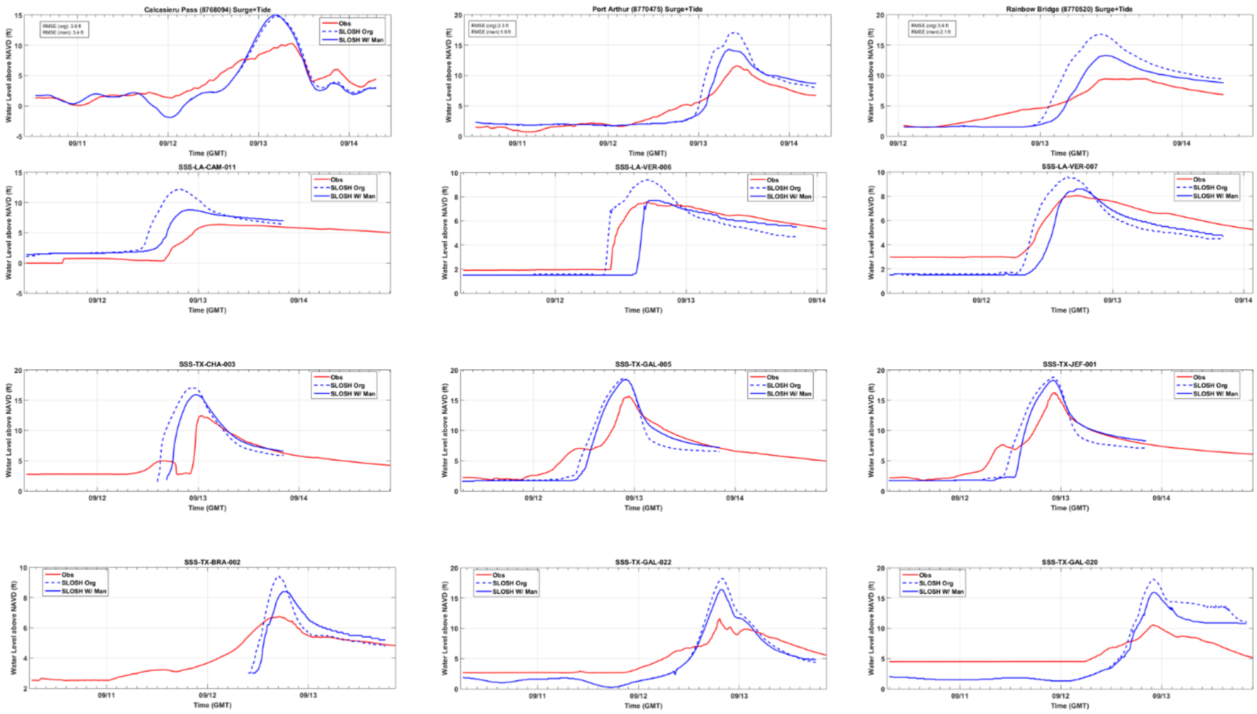

Figure 9. Time series of water level at NOAA tidal gauges and USGS sensors

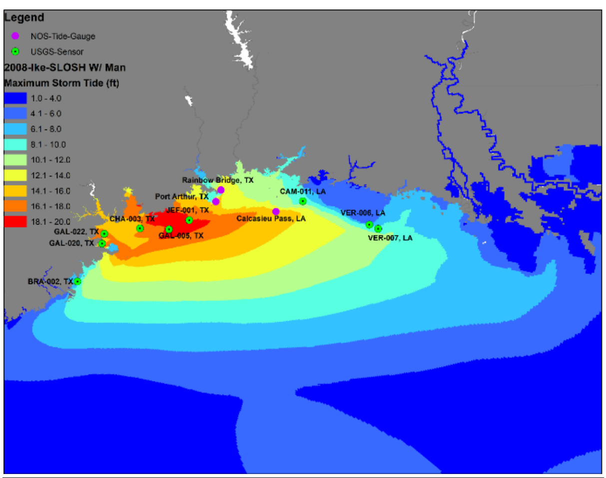

Figure 10. Locations of NOAA tidal gauges and USGS deployed sensors during Hurricane Ike

5. DISCUSSION AND SUMMARY

As discussed in the Introduction, the main purpose of this study is to address the over-forecast of overland storm surge heights and inundation extents in the SLOSH model by replacing the constant overland bottom friction with a spatially varying overland bottom friction. One popular and efficient way to do so is to use a Manning coefficient based on land cover data. This study utilized that method to create a spatially varying field of Manning coefficients which the SLOSH model then converted to the (now spatially varying) slip coefficients which it was designed to use.

In the test cases for hurricanes Rita in 2005 and Ike in 2008, there are significant differences in simulated inundation extents and peak storm surge heights between simulations from the original SLOSH and from the modified version (SLOSH W/ Manning). The comparisons with observed storm surges from NOAA tide gauges, overland USGS time series sensors, and HWM surveys for both hurricanes Rita and Ike indicate that incorporating the effects of land cover into the SLOSH model significantly improves the peak surge heights and extents of overland inundation. These comparisons show that the methodology introduced in this study to incorporate the effects of land cover into SLOSH model is beneficial.

6. REFERENCES

Arakawa, A.; Lamb, V.R. Computational design of the basic dynamical processes of the UCLA general circulation model. In Methods of Computational Physics; Chang, J., Ed.; Academic Press: New York, NY, USA, 1977; pp. 173–265.

Berg, R., 2009: Tropical Cyclone Report Hurricane Ike (AL092008) 1 – 14 September 2008.

Forbes, C., J. Rhome, C. Mattocks and A. Taylor, 2014: Predicting the Storm Surge Threat of Hurricane Sandy with the National Weather Service SLOSH Model. J. Mar. Sci. Eng. 2014, 2, pp. 437-476.

Haase, A. T., J. Wang, A. A. Taylor and J. C. Feyen, 2011: Coupling of tides and storm surge for operational modeling on the Florida coast. Proc. 12th Int. *Conf. on Estuarine and Coastal Modeling*, St. Augustine, FL, November 7-9, 2011; American Society of Civil Engineers, pp. 230-238.

Homer, C., C. Huang, L. Yang, B. Wylle, and M. Coan, 2004: Development of a 2001 national land-cover database for the United States. Photogrammetric *Engineering and Remote Sensing* 70, 829e840.

Knabb, R., D. Brown and J. Rhome, 2006: Tropical Cyclone Report Hurricane Rita 18 – 26 September 2005.

Liu, H., K. Zhang, Y. Li and L. Xie, 2013: Numerical study of the sensitivity of mangroves in reducing storm surge and flooding to hurricane characteristics in southern Florida. *Continental Shelf Research*, Vol. 64, August 1, 2013, pp. 51-65.

_____, A. Taylor and R. Schuster, 2015: Creating Inundation Guidance from NWS's Extra-Tropical Storm Surge Model. Preprints, 13th Symposium on the Coastal Environment, *95th Amer. Meteor. Soc. Annual Meeting*, Phoenix, AZ, 3.2, 7 pp.

Mattocks, C. and C. Forbes, 2008: A real-time event-triggered storm surge forecasting system for the state of North Carolina. *Ocean Modelling* 25, 95–119.

Jelesnianski, C. P., 1967: Numerical computations of storm surges with bottom stress. *Monthly Weather Review*, Volume 95, Number 11, pp. 740-756.

_____, and A. D. Taylor, 1973: A preliminary view of storm surges before and after storm modifications. *NOAA Technical Memorandum ERL WMPO-3*, Weather Modification Program Office, ERL, NOAA, U.S. Department of Commerce, Washington D.C., May, 33 pp.

_____, J. Chen and W. A. Shaffer, 1992: SLOSH: Sea, Lake and Overland Surges from Hurricanes. *NOAA Technical Report*, NWS 48, National Oceanic and Atmospheric Administration, U. S. Department of Commerce, 71 pp.

Platzman, G. W., 1963: The dynamical prediction of wind tides on Lake Erie. *Meteorological Monographs, Amer. Meteor. Soc*., 44 pp.

Resio,D.T. and J.J., Westerink, 2008: Modeling the physics of storm surges. *Physics Today* 61 (9), 33–38

Rodriguez, J. F., P. M. Saco, S. Sandi, N. Saintilan, and G. Riccardi, 2017: Potential increase in coastal wetland vulnerability to sea-level rise suggested by considering hydrodynamic attenuation effects. *Nature communications* 8 (1), 1-12.

Sheng, Y. P., A. Lapetina and G. Ma, 2012: The reduction of storm surge by vegetation canopies: three-dimensional simulations. *Geophysical Research Letters* 39, L20601.

_____, and R. Zou, 2017: Assessing the role of mangrove forest in reducing coastal inundation during major hurricanes. *Hydrobiologia* 803 (1), 87{103.

Taylor, A. and H. Liu, 2020: Latest Developments in the NWS' Sea Lake and Overland Surges from Hurricanes Model. 18th Symposium on the Coastal Environment, Boston, MA, *Amer. Meteor. Soc.*, 4.1, 8 pp.

Zhang, K., C. Xiao and J. Shen, 2008: Comparison of the CEST and SLOSH models for storm surge flooding. *Journal of Coastal Research* 24 (2 (242)), 489{499.

_____, H. Liu, Y. Li, H. Xu, J. Shen, J. Rhome and T. J. Smith, 2012: The role of mangroves in attenuating storm surges. *Estuarine, Coastal and Shelf Science*, Vol. 102-103, pp. 11-23.

Yang, D., A.J. Van der Westhuysen, J.R. Rhome, and C.L. Fritz, 2020: Efficient wave-surge coupling with SLOSH-wave for Hispaniola. Preprints, 18th Symposium on the Coastal Environment, 100*th Amer. Meteor. Soc. Annual Meeting*, Boston, MA, 4.3, 7 pp.