Vulnerability of National Park Service Beaches to Inundation during a Direct Hurricane Landfall: Cumberland Island National Seashore

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Abstract

Cumberland Island National Seashore, a barrier-island coastal park in Georgia, is vulnerable to the powerful, sand-moving forces of hurricanes. Waves and storm surge associated with these strong tropical storms are part of the natural process of barrier-island evolution and can cause extensive morphologic changes in coastal parks, leading to reduced visitor accessibility and enjoyment. The vulnerability of park beaches to inundation, and associated extreme coastal change, during a direct hurricane landfall can be assessed by comparing the elevations of storm-induced mean-water levels (storm surge) to the elevations of the crest of the sand dune that defines the beach system. Maps detailing the inundation potential for Category 1-5 hurricanes can be used by park managers to determine the relative vulnerability of various barrier-island parks and to assess which areas of a particular park are more susceptible to inundation and extreme coastal changes.

1. Introduction

Along much of the East Coast of the United States, hurricanes have been responsible for some of the most dramatic changes to our coastal environments – from the creation of large overwash deposits to the opening of new inlets. Strong winds associated with these tropical storms bring large waves and storm surge that force significant changes on fragile barrier islands, where the balance between island stability and rising water levels is maintained by dynamic changes in beach morphology. On developed barrier islands, hurricane-induced coastal change makes local infrastructure more vulnerable to failure. Even in our national coastal parks, where development is strictly managed, hurricanes threaten to destroy infrastructure that keeps the parks operational (e.g., unpaved roads, communications, park buildings) as well as to alter dramatically the beaches and dunes that provide visitors with the opportunity to observe wildlife and experience the interaction of the land and the sea.

The impact of a hurricane on a beach has been shown to be highly variable over both large and small stretches of coast (Stockdon et al., 2003) One section of beach may be largely unaffected by a storm, while an adjacent area experiences extreme coastal change associated with island overwash or breaching. This spatially variable response to storms is partly due to longshore variability of the pre-storm beach morphology combined with variability in the offshore physical forcing (Stockdon et al., 2007a). Using a storm-impact scaling model that compares the relative elevations of barrier-island morphology and storm-induced water levels, the potential vulnerability of a barrier island to extreme coastal change during a hurricane landfall can be defined (Sallenger, 2000).

A complete and comprehensive management plan preparing for a hurricane landfall, as well as plans for post-hurricane recovery, should be based, in part, on an assessment of what areas of the coast are most vulnerable. In order to help several of our coastal National Parks prepare for a possible hurricane landfall, the USGS, at the request of the National Park Service (NPS), has prepared an analysis of the vulnerability of Cumberland Island National Seashore (NS) beaches to inundation during a direct landfall. The results can be used to assess what areas of the park are most susceptible to extreme coastal change during a hurricane. These findings can also be compared to those from other NPS coastal parks to determine, in a relative sense, which parks are most at risk during strong tropical storms.

Cumberland Island NS is located in southern Georgia between the St. Mary's River to the south and St. Andrews Sound and the Satilla River to the north (Fig. 1). The 30 km of coastal park include wide beaches, marshes, and maritime forest and are composed of two uninhabited barrier islands, Cumberland Island and Little Cumberland Island (private property). The width of Cumberland Island is extremely variable, ranging from approximately 5.5 km in the northern portion of the island to less than 1 km toward the southern end. The east-facing beaches are open to the Atlantic Ocean and are most susceptible to the forces of approaching hurricanes.

2. Methods

2.1 Storm-Impact Scaling Model

A simple storm-impact scale that compares elevations of the most seaward sand dune to elevations of hurricane-induced water levels can be used to define the likely impact regime for an approaching hurricane (Sallenger, 2000). During a storm, the combined effects of 1) the astronomical tide, 2) storm surge (elevated water levels associated with the large winds and low pressures of a hurricane), and 3) wave runup (the super-elevation of the water surface at the shoreline due to waves, both the time-varying and time-averaged components) move the erosive

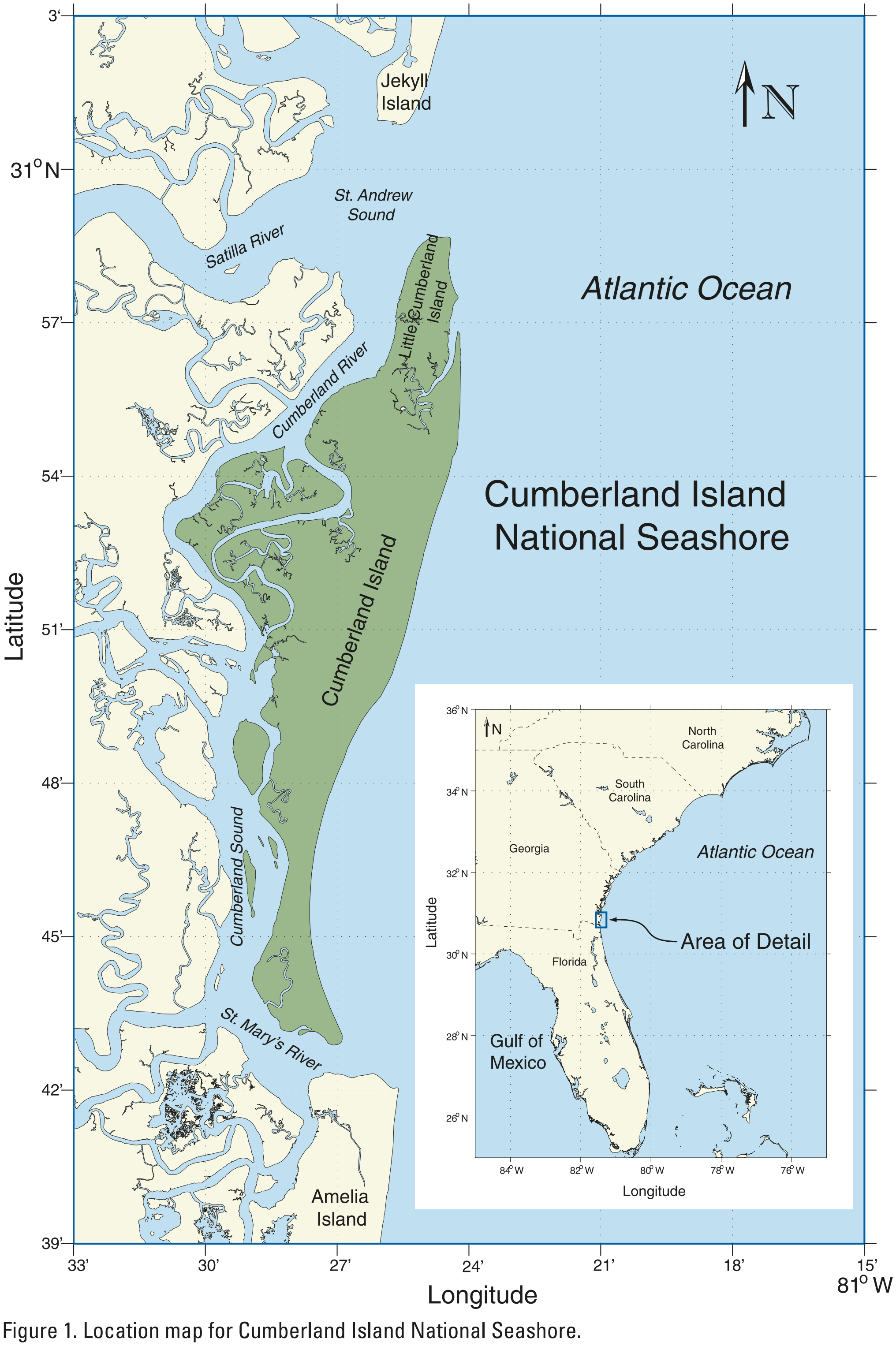

Figure 1. Location map for Cumberland Island National Seashore.

forces of the storm higher on the beach face than during typical wave conditions. The total elevation of these three parameters defines the maximum water level (R_{high}) attained during a storm, while the storm-induced mean-water level (R_{low}) can be defined by only storm surge and wave setup. These forces may reach the elevation of the base (D_{low}) and crest (D_{high}) of the most seaward sand dunes that define the landward limits of the beach system and represent the first line of defense for a barrier island in an approaching storm. Using these parameters, four storm-impact regimes, or thresholds for coastal change, maybe defined—*swash* ($R_{high} < D_{low}$), *collision* ($R_{high} > D_{low}$), *overwash* ($R_{high} > D_{high}$), and *inundation* ($R_{low} > D_{high}$) —to provide a framework for examining the general types and relative magnitudes of coastal change that are likely to occur during hurricanes (Sallenger, 2000; Stockdon et al., 2007a).

Here we focus on the most extreme of the four impact regimes, *inundation*, which occurs when the storm-induced mean-water level (R_{low}) exceeds the elevation of the crest of the most seaward sand dune (D_{high}). Within this regime, the beach system (foredune ridge and beach) is completely submerged, and net landward transport of sediment is likely to occur (Sallenger, 2000). Typically, larger magnitudes of shoreline retreat and beach erosion will occur when the beach is inundated due to the transport of sand in both the offshore and onshore directions (Stockdon et al., 2007a).

The predictive accuracy of the scaling model was tested by hindcasting the likely impact of Hurricanes Bonnie and Floyd (Stockdon et al., 2007a) and of Hurricane Ivan (Stockdon et al., 2007b). For Hurricane Ivan, the overall hindcast accuracy of the model in predicting one of the four regime types was 68%. The sensitivity of the model within the inundation regime was 51% (Stockdon et al., 2007b). Underprediction errors were likely due to profile evolution of the low-lying barriers during the landfall of this Category 4 storm. In order to use this model in a predictive mode to examine the potential for inundation during a future hurricane landfall, accurate estimates of both the dune parameters and the expected hurricane-induced mean-water level are needed.

2.2 Dune Elevation

The morphology of the beach and dunes at Cumberland Island NS was mapped based on an airborne lidar topographic survey conducted on January 16, 17, and 18, 2006, by the U.S. Army Corps of Engineers (USACE) CHARTS system. GPS-based lidar surveys provide an efficient method for collecting high-resolution data of subaerial topography with sufficient accuracy (root-mean-square vertical accuracy = 15 cm) to resolve the spatial details of sand-dune elevation and position (Sallenger et al., 2003).

The elevation of the foredune crest (or, in the absence of a dune, the beach berm) was extracted every 20 m along the coast of Cumberland Island NS from cross-shore profiles of lidar topography (Fig. 2). An automatic algorithm was used to select the peak of the most seaward dune within a prescribed beach width (here, 175 m). The results were then manually checked to ensure the extraction of a consistent feature defining the landward extent of the beach system (Fig. 3). The cross-island width of Cumberland Island is very large in some areas of the park, allowing for large inland dune complexes. The storm-impact scaling model is focused on the vulnerability of the beach system, which is defined by the location of the most seaward dune. Accordingly, interior dunes, regardless of their elevation, were not considered in this analysis.

2.3 Storm Surge

In this analysis, R_{low} is represented only by the storm surge. Wave setup was not considered because predictions of wave conditions (height and period) for a generic hurricane of each category are not currently available. The predicted elevations of storm surge for Saffir-Simpson Category 1-5 hurricanes were extracted from the NOAA SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model, a real-time forecast model for hurricane-induced water levels for the Gulf and Atlantic Coasts. The numerical model is based on linearized, depth-integrated equations of motion and continuity (Jarvinen and Lawrence, 1985). Storm surge is modeled by simulating the conditions of each category storm approaching the coast from different angles and at varying speeds. Changes in maximum surge elevations are forced by time-varying wind-stress and pressure-gradient forces that depend on hurricane location, minimum pressure, and size measured from the eyewall out to the location of maximum winds (Jarvinen and Lawrence, 1985). The maximum surge within each grid cell is defined as the Maximum of the Maximum Envelope of Water (MOMs) and represents the worst-case, localized surge that will occur for landfall in a given location, not what would occur along the entire coast for a single storm. The results are location specific, accounting for local water depths, proximity to bays and rivers, etc., and are accurate to ± 20% of the calculated value (NOAA, 2007). Errors in the SLOSH model can arise from differences between the parametric wind models, which force SLOSH, and the actual hurricane wind field (Houston et al., 1999), as well as discrepancies between the coarse model grid and the real topography and bathymetry over which the storm will travel.

For Cumberland Island NS, the maximum surge at the shoreline was extracted from the MOMs results for the Brunswick model grid (Fig. 4, left). Maximum, open-coast surge values were extracted at the location of the January 2006 lidar-derived, mean-high-water (MHW, 0.68 m NAVD88) shoreline position (Fig. 4, right). The Brunswick SLOSH-model grid has an approximate cell size of 1.4 km to 1.8 km along the shoreline of Cumberland Island NS. In locations where grid resolution resulted in anomalously low values because the barrier island was not fully resolved, the most nearshore grid cell representing conditions seaward of the barrier island was chosen.

3. Inundation Vulnerability

The potential inundation, I, of the beach system was defined every 20 m along Cumberland Island NS by calculating the difference between the elevations of SLOSH-modeled storm surge (R_{low}) for each hurricane category and of lidar-measured dune crests (D_{high}) (Fig. 5). Negative values (blues) indicate that

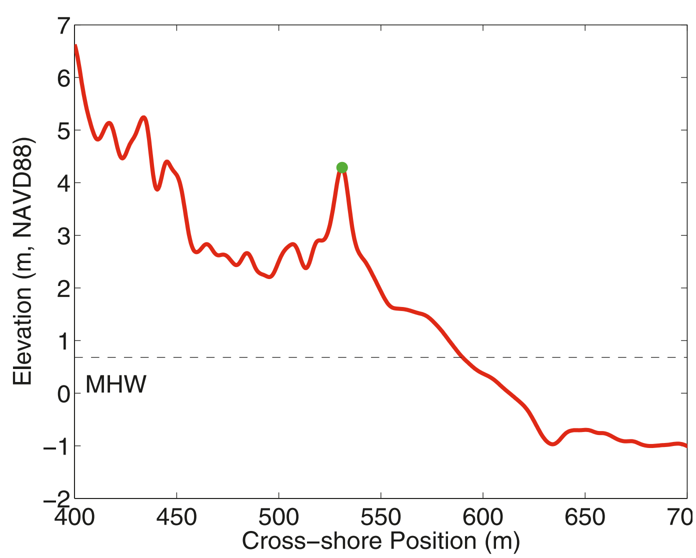

Figure 2. Cross-shore profile of lidar data from Cumberland Island NS showing the location of the most seaward sand dune. The ocean is located to the right.

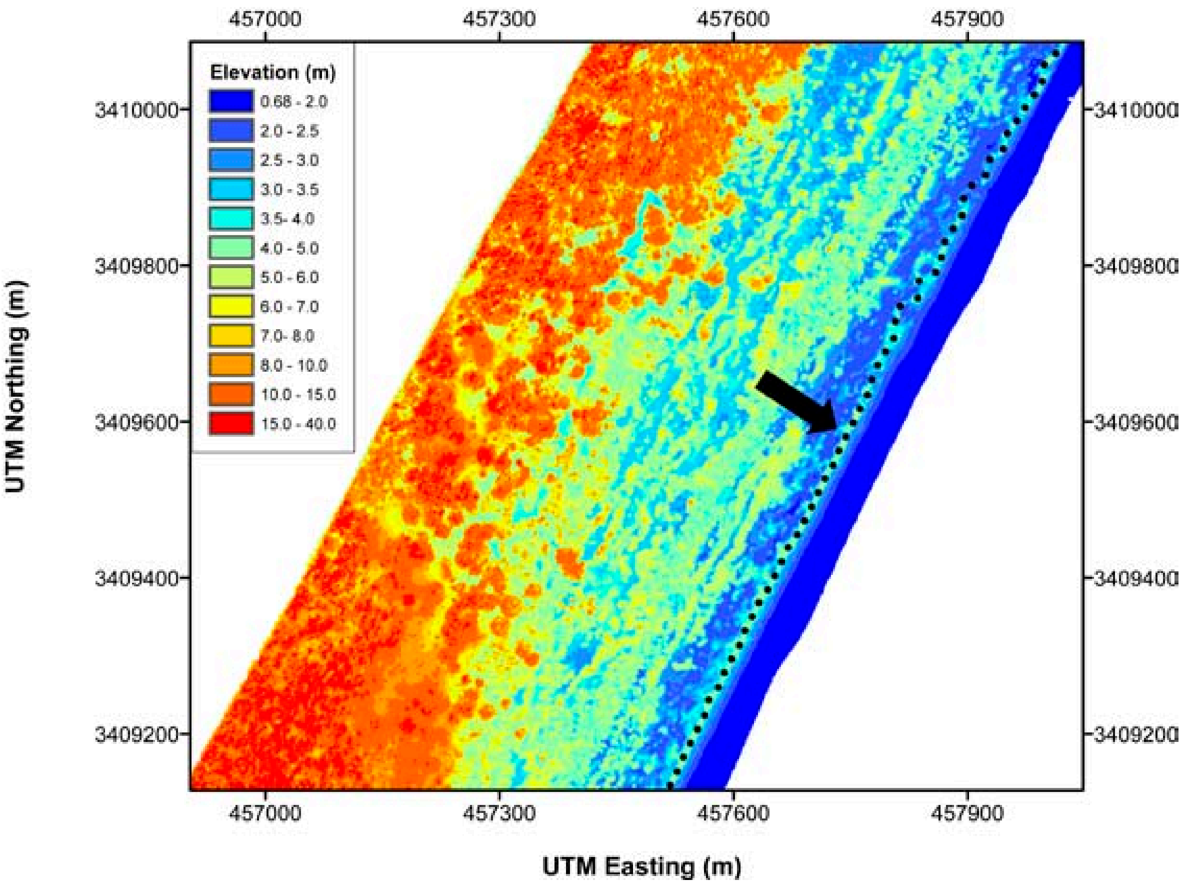

Figure 3. The extracted crest of the dune line for approximately 1.3 km of the Cumberland Island NS coast, superimposed on the lidar topography. The arrow refers to the location of the profile shown in Figure 2.

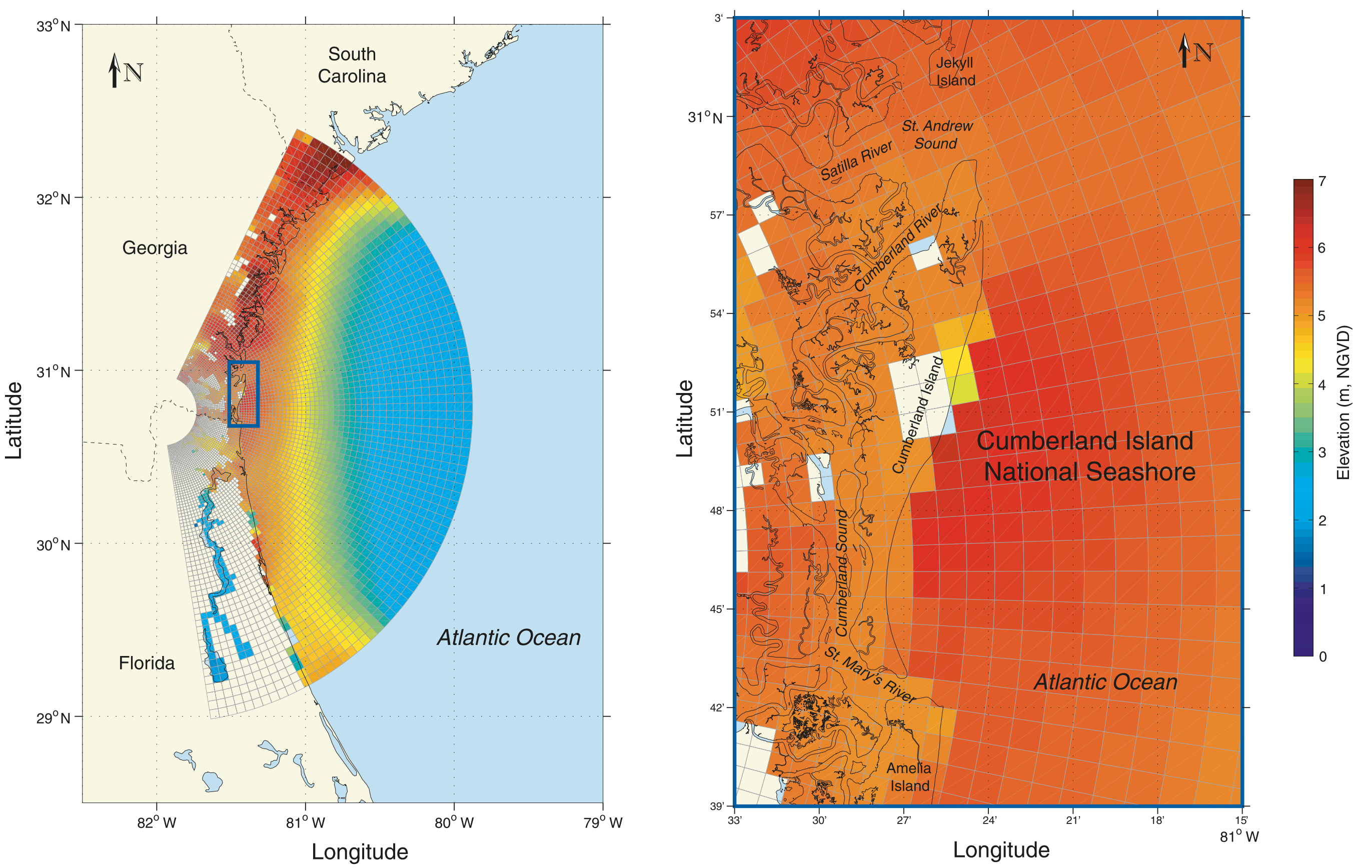

Figure 4. SLOSH-model results for a Category 3 hurricane for the Brunswick model grid (left) shows the variability of modeled surge values along the coast. Maximum, open-coast surge levels for Category 1-5 hurricanes were extracted from the SLOSH grid along the Atlantic shoreline of Cumberland Island NS (right).

water levels are predicted to be lower than the dune crest and that a particular section of beach is not likely to be inundated during the direct landfall of a hurricane. Positive values (reds) signify areas where the beach is more likely to be inundated by storm surge. These estimates assume landfall at mean astronomical tide and do not include the effects of wave setup, which, during strong storms (Category 3 and above), may increase the storm-induced mean-water level by more than 30% above that due to storm surge alone. This would increase the vulnerability to inundation. Additionally, the maps represent the vulnerability of the beach system as it was at the time of the January 2006 lidar survey. Major changes to beach morphology, such as those caused by large storms and hurricanes, may change the future vulnerability of this stretch of coast.

For the direct landfall of a Category 1 storm, 10% of the Cumberland Island coast is vulnerable to inundation, compared to over 97% during a Category 5 storm. The vulnerability for a single category storm is highly variable along the length of the park due to spatial variations in the height of the frontal dune. The mean elevation of D_{high} is 4.19 m NAVD88 with substantial longshore variability, standard deviation, σ, = 1.49 m (Fig. 6). The surge is much less spatially variable: alongshore averaged surge for a Category 1 hurricane was 2.99 m NAVD88 (σ = 0.09 m), and the average surge for a Category 5 storm was 7.27 m (σ = 0.30 m) (Fig. 6). While the variability of I and D_{high} dominate the signal along Cumberland Island, the lower dunes on the northern end (6.5 km) and central third of the park (Fig. 6) make these locations more susceptible to inundation: generally, $R_{low} > D_{high}$ for these areas for Category 2 and higher storms.

4. Rates of Recent Shoreline Change

Detailed analysis of the historic (150-yr) rates of shoreline change, calculated using the horizontal position of the MHW shoreline from four time periods (mid-1800s, early 1920s, early 1970s, and 1999), along Cumberland Island NS shows that over 80% of the shoreline along the two islands is accreting with a 5.5-km stretch of erosion located ~3 km north of Stafford Beach (Morton and Miller, 2005). The short-term shoreline-change rate calculated over an approximate 27-yr period shows a similar pattern of erosion and accretion; however, the northern 3.5 km of Cumberland Island were also found to be eroding. Details of the calculations and specific rates of change for both historic and short-term periods can be found in Miller et al. (2005).

Rates of recent shoreline change were calculated between the October 1999 shoreline used in the Morton and Miller (2005) analysis and the modern shoreline position as defined using the January 2006 lidar survey that was the basis of the inundation analysis. From each lidar survey, datum-based (MHW = 0.68 m) shoreline positions were extracted every 20 m along the coast using techniques described in Stockdon et al. (2002). Horizontal movement of the shoreline, calculated as the difference in position between 1999 and 2006, showed accretion over 80% of this 30-km stretch of coast (Fig. 7). The largest magnitudes of change were observed along the short (2.5 km) beach of Little Cumberland Island and at adjacent inlets. Excluding change on Little Cumberland Island, the mean shoreline change over the 6.25-yr time period was 12.40 m and the standard deviation was 19.50 m. The magnitude of shoreline change ranged from 120.70 m of accretion to 105.31 m of shoreline retreat. The mean, short-term-change rate over the 6.25-yr period was 1.98 m/yr (σ = 3.10 m/yr), again excluding the inlet effects near Little Cumberland Island. The pattern of this short-term-change rate was consistent with the long-term (~150 yr) rate found by Morton and Miller (2005): the system is dominated by accretion with a 5-km stretch of eroding coast located just north of the center of the longshore extent of the park (Fig. 7). Detailed rates of change and associated error bars for the length of the park can be found at http://coastal.er.usgs.gov/nps-beaches/.

5. Discussion

The vulnerability maps detail the worst-case surge scenario for each location along the coast. For open-coast barrier islands, maximum surge typically occurs to the right of landfall under the eyewall and decreases with distance away from the center of the storm. Consequently, the worst case for any given storm is localized and will not occur along the entire coast of Cumberland Island NS. The map shows areas that are most likely to be inundated by storm surge should the hurricane make landfall immediately to the south of that particular location.

If the beach system is inundated, the dune will be overtopped by storm surge. Strong waves and currents may transport large amounts of sand landward across the island. These types of changes have been shown to be more long-lasting because sand removed from the beach face does not typically return in the years following storm landfall (Stockdon et al., 2007a). In the southern portion of the park, where the width of the beach system approaches the width of the island, the currents associated with inundation may cross the island and create new or expose relict inlets.

Acknowledgments

We thank Rebecca Beavers and Mark Borrelli (NPS) for their assistance in the development of this project. John Fry, Tony Curtis, and Linda York (NPS) provided early reviews of the map products. The lidar data were collected by Jeff Lillycrop (USACE) and his CHARTS team. We also thank Betsy Boynton, Kara Doran, Kristy Guy, Peter Howd, Abby Sallenger, Jolene Shirley, and Charlene Sullivan (USGS) for their contributions to this study. This work was funded by National Park Service, Natural Resource Program Center.

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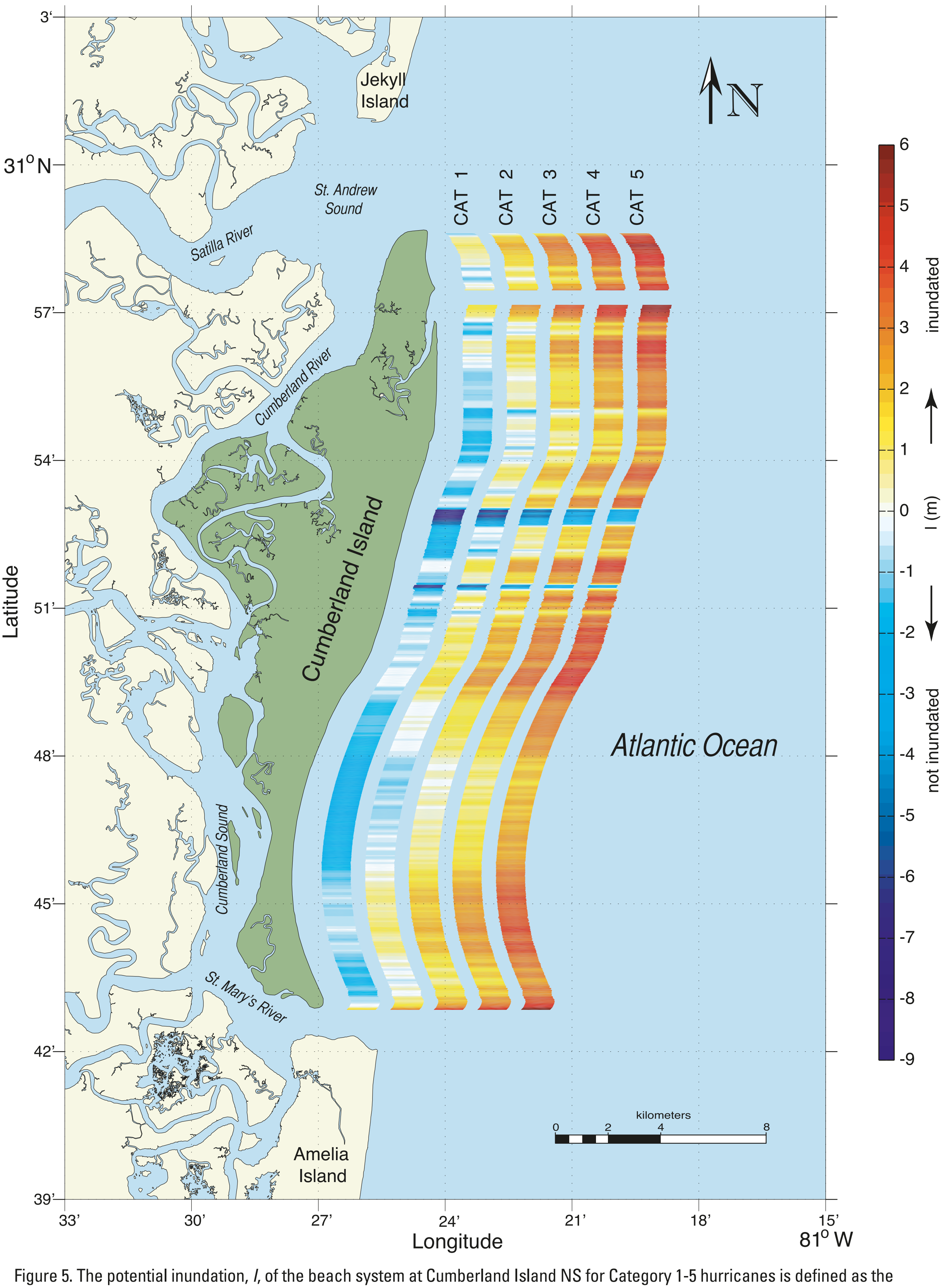

Figure 5. The potential inundation, *I*, of the beach system at Cumberland Island NS for Category 1-5 hurricanes is defined as the difference between R_{low} and D_{high}. A 200-m smoothing window was applied to the data before plotting. Positive values indicate that modeled storm surge exceeds the elevation of the dune crest, suggesting that the beach system is more vulnerable to inundation and the associated extreme coastal changes. A larger version of this map can be downloaded from http://coastal.er.usgs.gov/nps-beaches/.

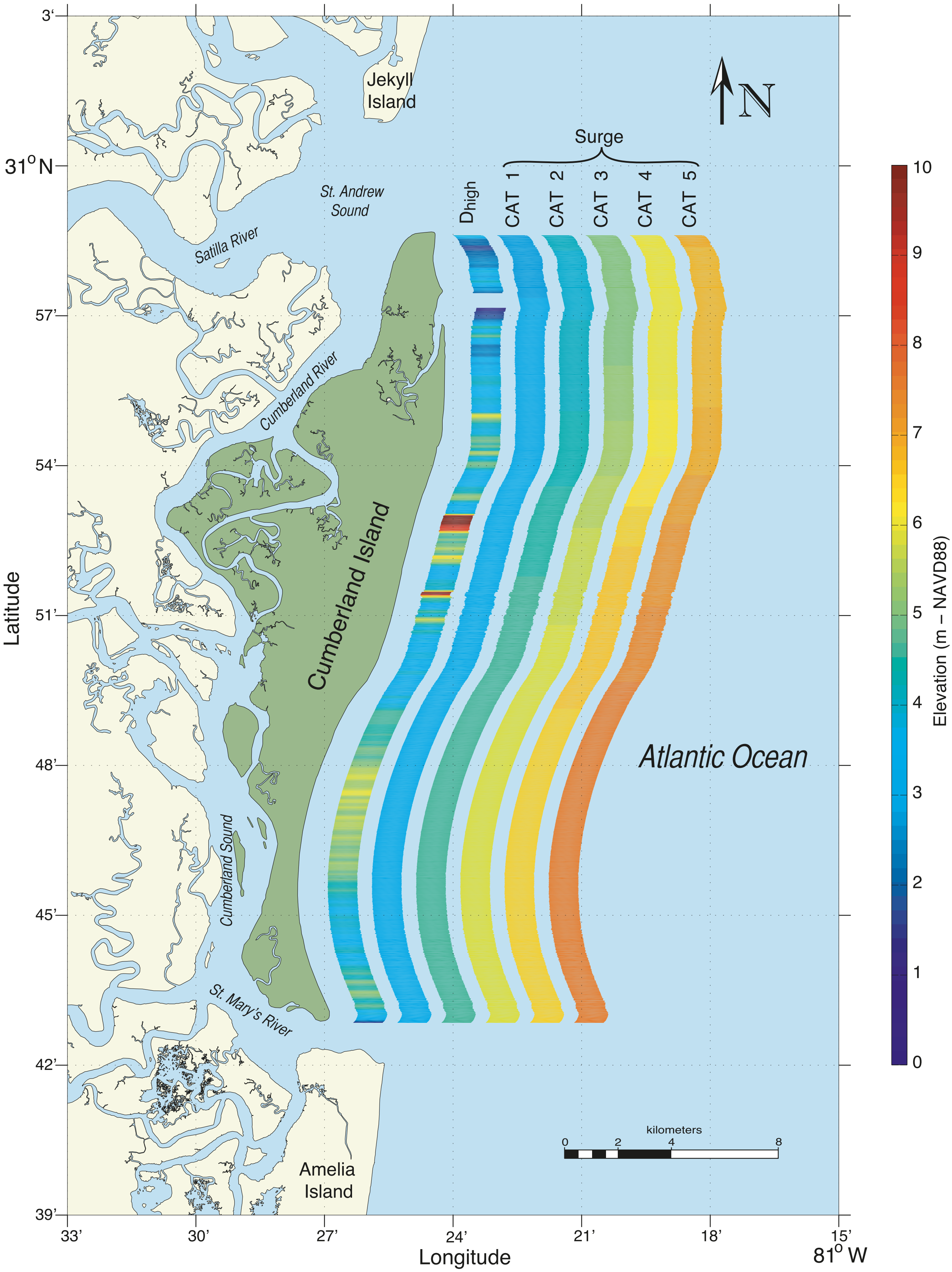

Figure 6. Dune elevations (D_{high}) for Cumberland Island NS were measured from a lidar topographic survey conducted on January 16, 17, and 18, 2006. The surge values (R_{low}) for Category 1-5 hurricanes were extracted from the NOAA SLOSH model and represent the open-coast 'maximum of the maximum.' A larger version of this map can be downloaded from http://coastal.er.usgs.gov/nps-beaches/.

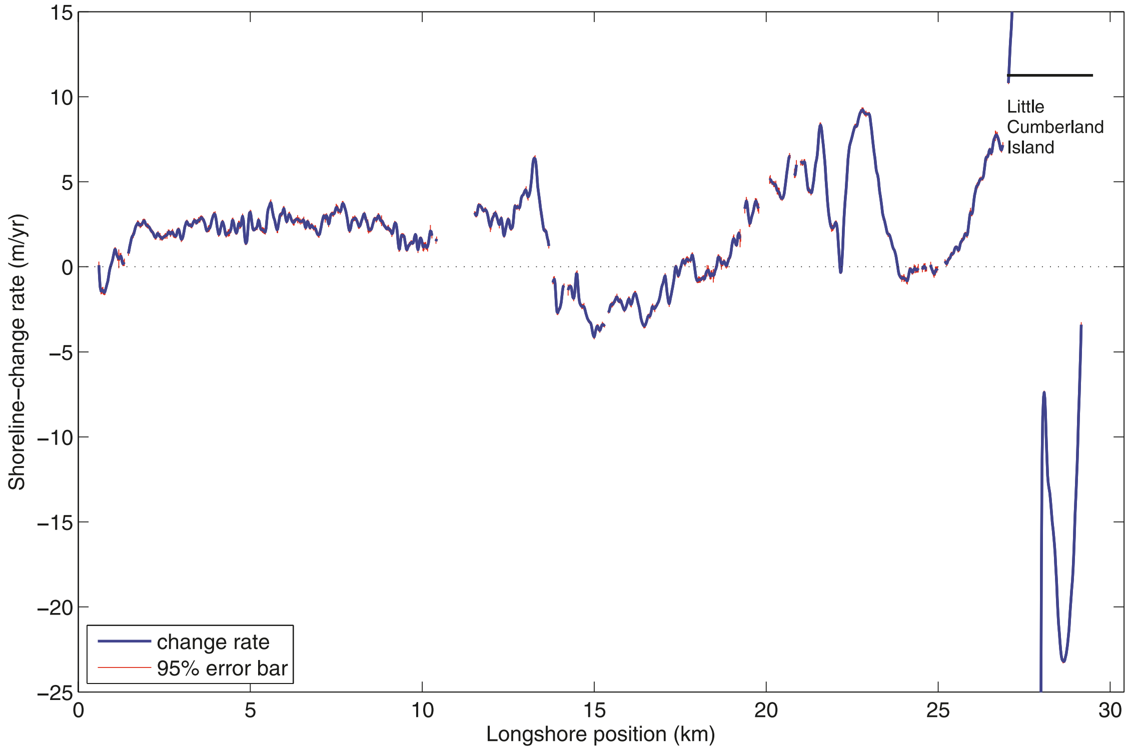

Figure 7. Short-term (6.25-yr) rates of shoreline change for Cumberland Island NS. Data were smoothed with a 100-m window. Negative values indicate erosion. Away from the effects of inlets, the mean rate is 1.98 m/yr.

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