East Carolina University

Identify Cultural Resources Sites Affected by Sea Level Rise at Cape Hatteras National Seashore

Final Report to US National Park Service for Piedmont-South Atlantic Cooperative Ecosystems Studies Unit Task Agreement No. P13AC01432

Dr. Thomas R. Allen, Principal Investigator
1-11-2017
*Current address: Department of Political Science & Geography,
Old Dominion University, Norfolk, VA 23529
Email: tallen@odu.edu; Tel. (757) 683-6059

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1. INTRODUCTION

Cape Hatteras National Seashore (CAHA), located along the Outer Banks, was established in 1937 to preserve cultural and natural resources of national significance. This is challenging task as this area is renowned for dynamics associated with storms and sea-level rise, including high erosion and storm surges. The enabling legislation for the CAHA as well as the Code of Federal Regulations 36 CFR parts 1-199 and the Park Compendium provide specific instructions and guidance on how the park can be managed by the National Park Service (NPS 2016). The focus of this project was vulnerability assessment of historic structures, some of which have already been relocated as a result of inundation and shifting shorelines. The project used a multi-hazard framework approach to sea level rise threats, includingshoreline change, inundation and storm surges, and scenario uncertainty. In addition, the spatial context of these hazards necessitated the consideration of planning horizons, surrounding jurisdictions and the potential for tipping points in physical vulnerability as relative sea level rises. The project also conducted a detailed documentation of data processing and analytical protocols, so as to promote replicability and future repeatability in CAHA or other NPS sites.

The CAHA shares boundaries with federal, state, and local properties including that of the U.S. Fish and Wildlife Service, the North Carolina Division of Transportation (NCDOT), and Dare and Hyde counties. The establishment of these jurisdictions has influenced where coastal development has occurred as well as the regulations that have guided activities throughout the region. Although the type and level of management vary among the jurisdictions, all of the coastal development that currently exists either within or adjacent to the CAHA is potentially subject to impacts from multiple hazards. Therefore, it is important to implement effective hazard mitigation planning in order to reduce both the short- and long-term risks that hazards pose to the park cultural resources.

Recognizing the vulnerability of historic structures, the NPS and East Carolina University entered this task agreement to assist park managers with long-term planning. Utilizing Geographic Information Systems (GIS) and available data and common analysis methodologies, the susceptibility of 27 historical structures to coastal erosion, storm surge, and sea level rise was evaluated. Results of the study provide park managers with susceptibility metrics for each structure as well as estimated timelines for potential impacts. Such risk assessment gives invaluable information that can be used to later identify possible mitigation needs and adaptation measures and aid future budget planning efforts. In addition, the assessment gives a useful context to broader community vulnerability and coastal development located in adjacent areas of the Outer Banks.

Coastal erosion in particular regions has increased the vulnerability of some properties to coastal storm damage and left others as uninhabitable. Projections of sea level rise help indicate the enhanced susceptibility of property to coastal hazards. Even more concerning is that the access to the island by tourists and residents is largely determined by NC Highway 12. Transportation along this critical roadway has been interrupted on many occasions following hurricanes (Isabel (2003), Irene (2011) and Sandy (2012)) as well as nor'easters. The management and maintenance of this transportation corridor has been complicated by differing stakeholder interests, including those of federal and state agencies as well as local citizens.

Prior directly relevant assessments of sea level rise include Titus and Wang (2008) and the NC Sea Level Rise Risk Management Study (SLRRMS). Titus and Wang (2008) implemented an analysis of regional vulnerability, although this was conducted at a coarse, regional scale. The NC SLRRMS study sought to evaluate flood zones and potential damage from flood event, and as such focused on modeling floodplains. Neither study undertook the integration of multiple hazard vulnerabilities or used the fine spatial resolution to focus on non-floodplain historic sites and structures. Nonetheless, both provide valuable context. Some other studies informed this work. The NC SLRRMS assimilated known data sources and process rate measurements for a pilot study on the Outer Banks to verify robustness of inundation modeling methodology. This pilot study focused on the Outer Banks and mainland Dare County, specifically on Pea Island. The thesis by Gore (2012) assessed the error, uncertainty, and sensitivity of the Sea Level Affecting Marshes Model (SLAMM) used in the methodology of the SLRRMS study. Along with erosion rates from long-term shoreline mapping by the NC Division of Coastal Management and several studies evaluating the subsidence and relative sea level across the region, these prior studies provided data and a process-based foundation for the vulnerability assessment herein.

2. STUDY AREA

The boundary of the CAHA was used as the extent of this study area (Figure 1). The Seashore is bounded by "Whalebone Junction" in Nags Head, where U.S. 264 intersects with N.C. 12, and continues south including Hatteras Island and Ocracoke Island. Hatteras Island is the longest barrier island (~80 km) in the chain that is commonly referred to as the Outer Banks. This barrier-island system separates the Atlantic Ocean from the expansive estuaries of the Albemarle-Pamlico Estuarine System (APES).

The width of Hatteras Island north of Cape Hatteras varies from ~1.2 km south of Salvo to less than one-tenth of a kilometer, just north of Buxton. A nourishment project is currently planned for 2017 in this area. The communities of Buxton and Frisco are located along the estuarine side stretching for approximately 11 km. Here the island has its maximum width of ~6 km from Cape Point to the sound. The island narrows to less than 150 m before widening to nearly two kilometers where the community of Hatteras is located before the island terminus at Hatteras Inlet. Ocracoke Island is located on the southern side of the Hatteras Inlet and extends for ~26 km; Island widths range from ~180 m to ~2.8 km where Ocracoke Village is located.

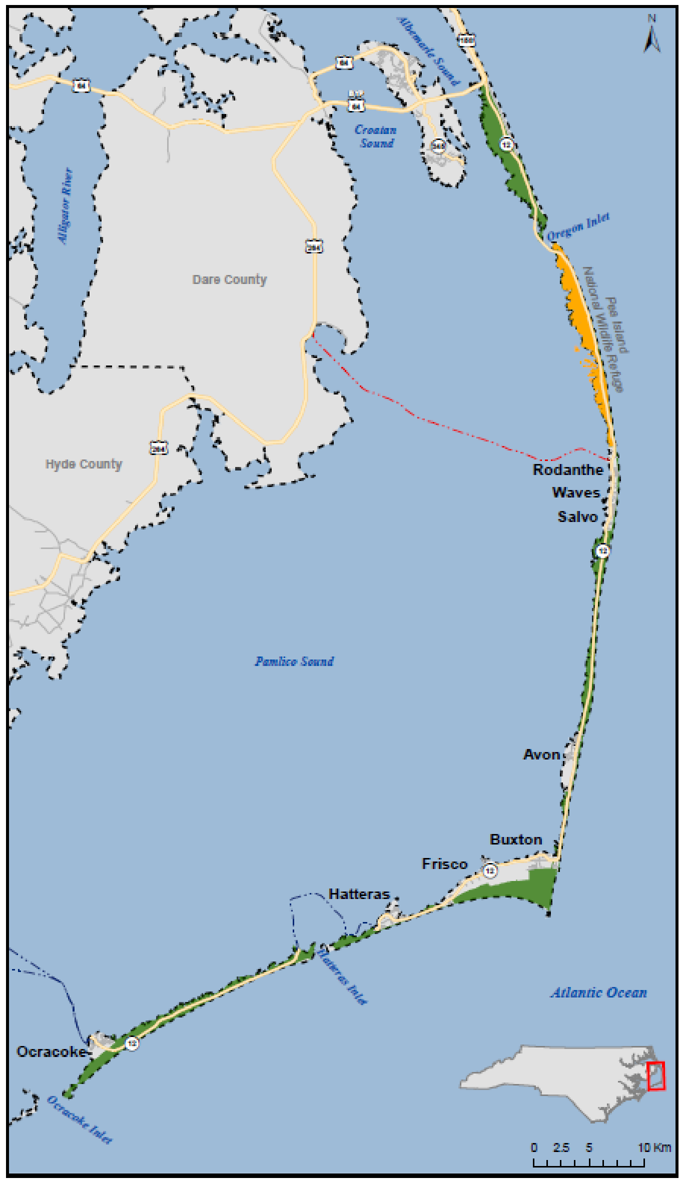


Figure 1. Study area map. The study area (CAHA) is located along the Outer Banks.

Diamond Shoals is the submerged sandy shoal that extends from Cape Hatteras to the shelf edge, nearly 16 km. This and other treacherous shoals along the NC coast have yielded countless shipwrecks, giving the infamous "Graveyard of the Atlantic" name to the region. Diamond Shoals also divides the coastal ocean waters into two embayments known as Hatteras Bay to the north and Raleigh Bay to the south.

As Riggs (2011) notes, the near-perpendicular bend of Hatteras Island causes waves, winds and currents to often impact the coast differently along the two sides of Cape Hatteras, and this must be remembered as hazard impacts are considered.

3. MULTI-HAZARD VULNERABILITY ASSESSMENT METHODOLOGY

3.1 Sea Level Rise Inundation

Based on a dialogue with the NPS, this project focused on sea-level rise and related hazards in the next 50 years. This section reviews the overall multi-hazard approach in series and combination, and describes the scenarios adopted and outlines the reporting output and structure. First, a timeframe was chosen so as to provide a long-range view. With the moderate (50-year) time frame, it was believed to to be reasonable to employ morphostatic scenarios (i.e., inundation use of static rather than dynamic landform changes that would reflect feedbacks and future changes of landforms). Such "morphdynamic" modeling is complex and difficult for this coupled human-natural system and barrier spit and cape complexes Allen et al. 2012). Analyses were consistent with prior SLR vulnerability assessments in North Carolina, notably the NCSLRRMS and its sea-level-rise scenarios of 20 cm, 40 cm, 70 cm, 100 cm and 140 cm. These rise amounts are also aligned with the 2009-2010 NC Science Panel of the Coastal Resources Commission. Within the region and its relative SLR rate of 3.5-4.5 mm/yr, these scenarios provide assessment across a range of uncertainty in sea-level rise, which may include changes related to many local and ocean factors. Also, the higher rise amounts (e.g., 100- and 140 cm) may also be used to assess the possible effects of faster acceleration over a shorter time scale (NC CRC Science Panel 2010).

An important consideration involving coastal elevation data quality also influenced this study. At the outset of the project, only the first generation of remotely sensed airborne elevation data were available. New elevation data obtained in 2015 from the NC Floodplain Mapping Program provided significant improvement in vertical accuracy and spatial resolution over prior data. Data quality was limited to nominal root mean square error of approximately 30 cm +/- vertical accuracy. This level of accuracy would constrain, largely preclude, consideration of inundation for near-term sea level rise of values <= 20-40 cm height, overestimating inundation extent. In order to maximize the quality of the assessment, the project timeframe was extended to use the latest elevation data from NC Floodplain Mapping. The new "QL2" quality data provided a significant improvement in the vertical accuracy of DEMs (<10 cm RMSE and up to 14 LiDAR points per square meter), resulting in more reliable and finer resolution of potential inundation maps. In addition, these LiDAR DEMs included improved hydro-correction (reflecting artificial drainages, culverts and conduits, and flow paths), characterization of finer-scale topographic features (e.g., dune and beach berm crests and swales) and also reduced error in adjoining marshes and dense foliage such as maritime forests and hammocks.

A first-order estimate of seal level rise and potential inundation can be derived by "bathtub" inundation maps. Utilizing widely adopted inundation modeling techniques, NOAA's Office for Coastal Management produced an online Sea Level Rise Viewer (NOAA 2016) and provides a variety of ancillary GIS data and visualizations. A core product includes raster grids of potential 1ft, 2ft, and 3ft sea level inundation. The viewer is a tool that uses nationally consistent LiDAR elevation data sets and datum analyses to evaluate the broad-scale impacts of sea level rise for long-term planning. Data and maps provided can be used at several scales to help gauge trends and prioritize actions for different scenarios. The NOAA OCM SLR Viewer provides sea level rise inundation maps for 1ft, 2ft, and 3ft above current Mean Higher High Water (MHHW). These data tiles were obtained down to Level ID 11 (~1:18,055) and overlaid onto an ESRI orthophoto basemaps and CAHA building footprints. Each historic district was mapped into a layout at 1:5000 scale for intercomparison. Below, each of the CAHA historic districts is presented in visual format using ArcGIS and the downloaded NOAA SLR inundation grids. Other grid products include potential marsh responses and uncertainty flags.

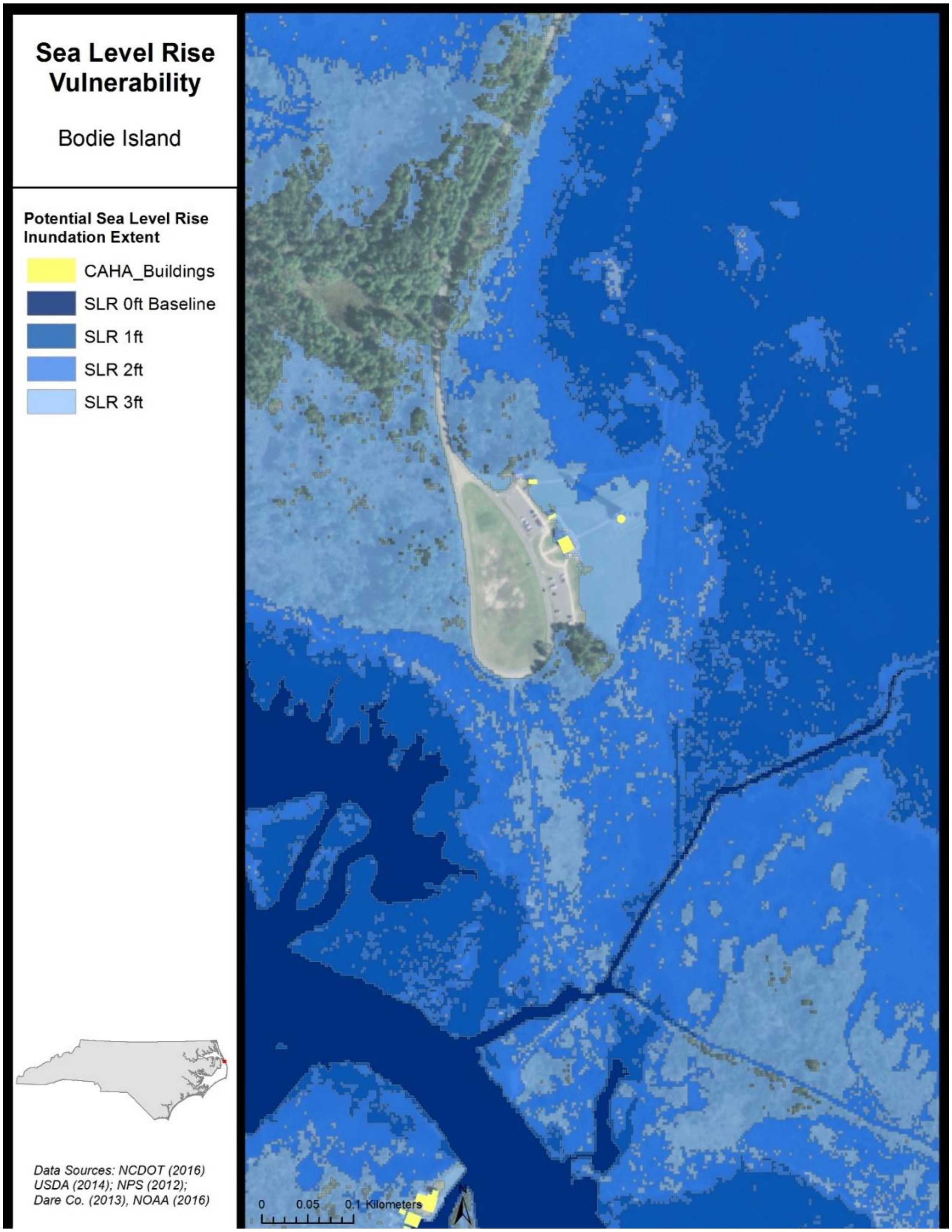


Figure 2. Potential relative SLR inundation at Bodie Island for 1, 2, and 3 ft. sea level. The site illustrates high susceptibility to flooding with static SLR, marsh loss, and impacts to accessibility at 1-2ft. of rise.

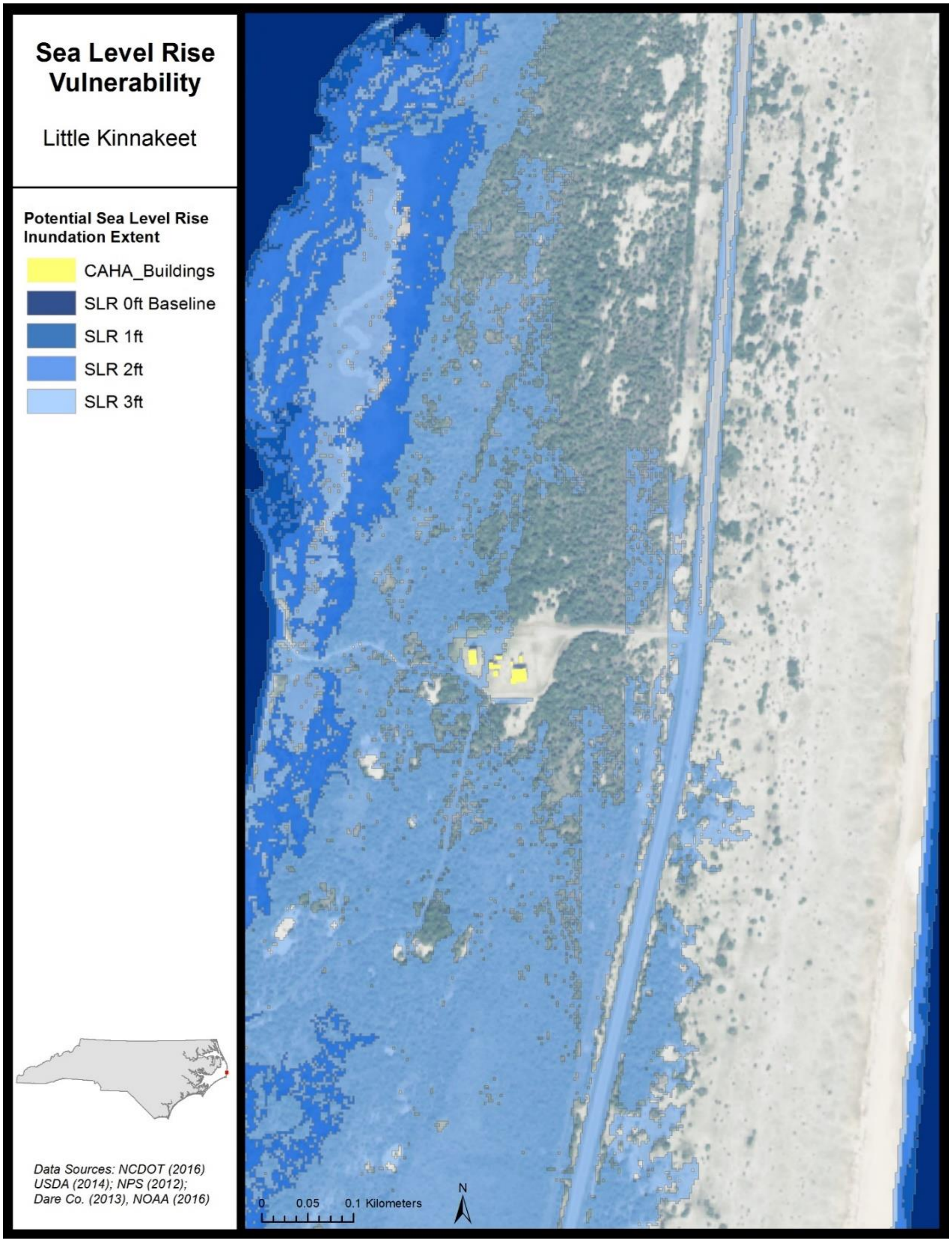


Figure 3. Potential SLR inundation at Little Kinnakeet district depicts soundside and surrounding flooding impacts to roads above 2-3ft relative sea level.

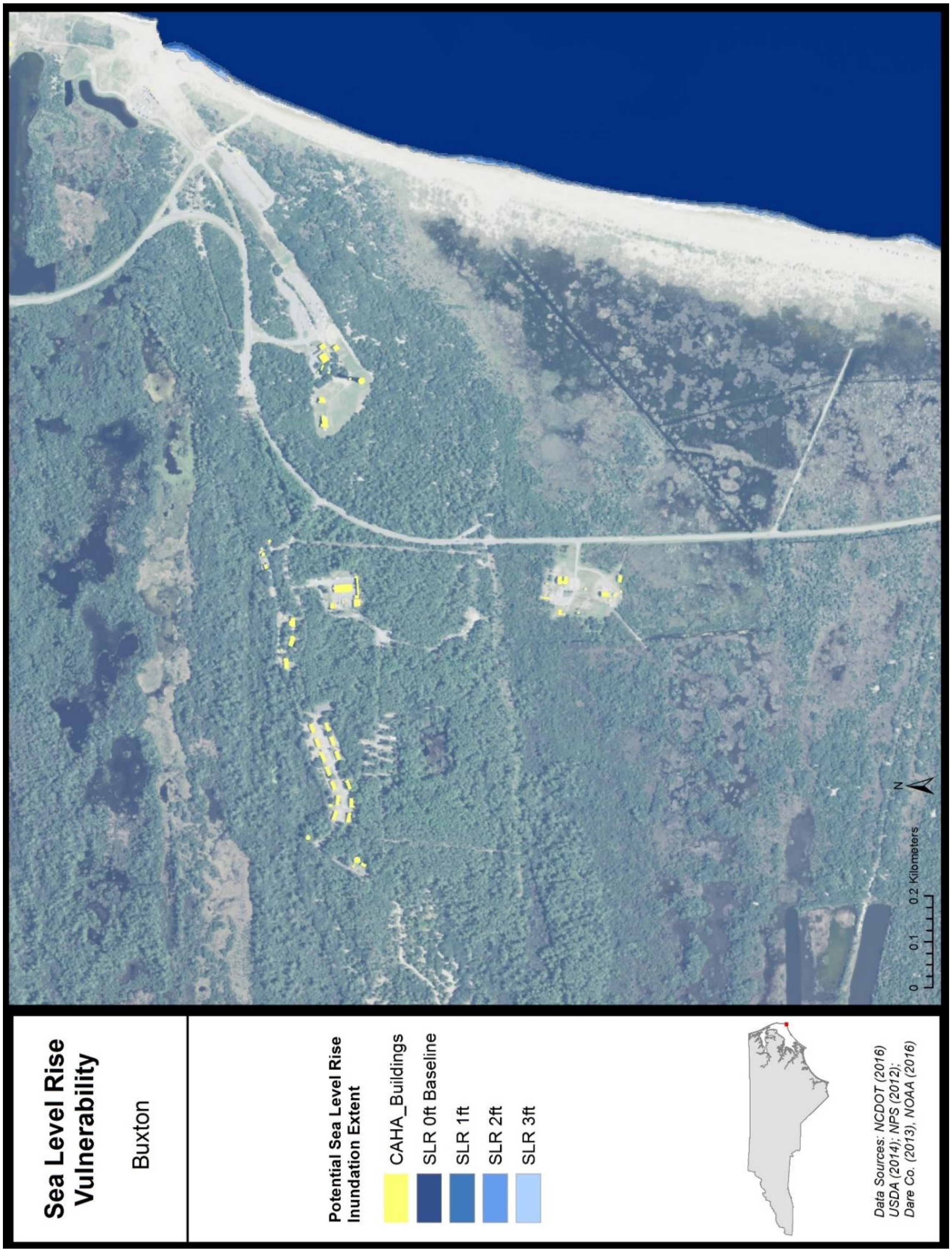


Figure 4. Potential SLR inundation at Cape Hatteras Light shows limited connected inundation. This representation, however, does not account for ground water elevation related flooding and ponding interactions, such as have occurred since fall 2015 Hurricane Joaquin and 2016 Hurricane Matthew associated rainfall.

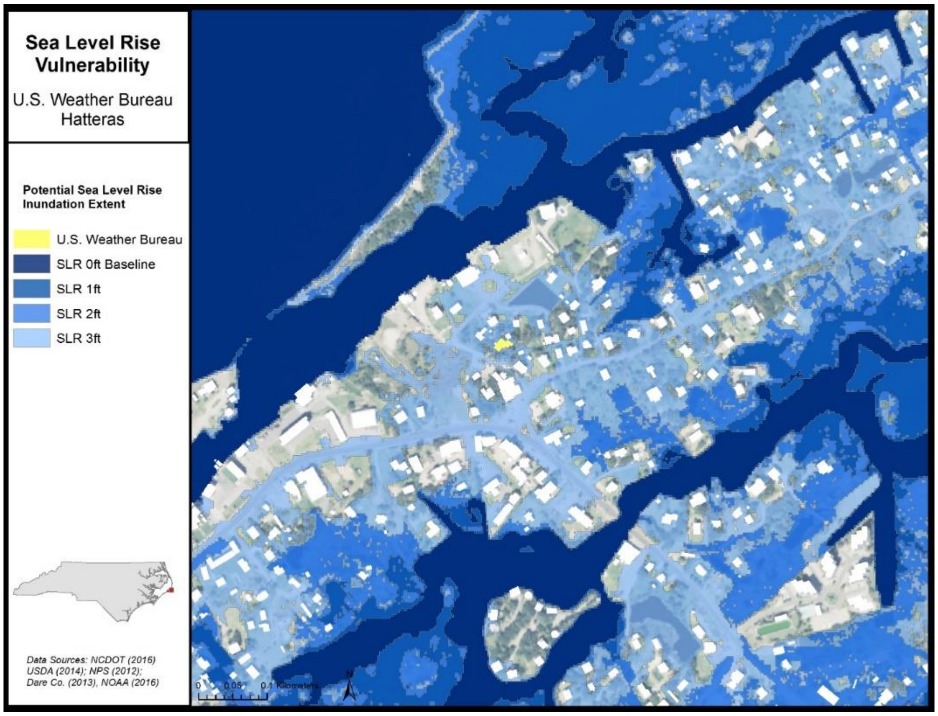


Figure 5. Potential SLR inundation at the Hatteras Weather Bureau shows wide backbarrier potential flooding and accessibility impacts at 2-3ft levels.

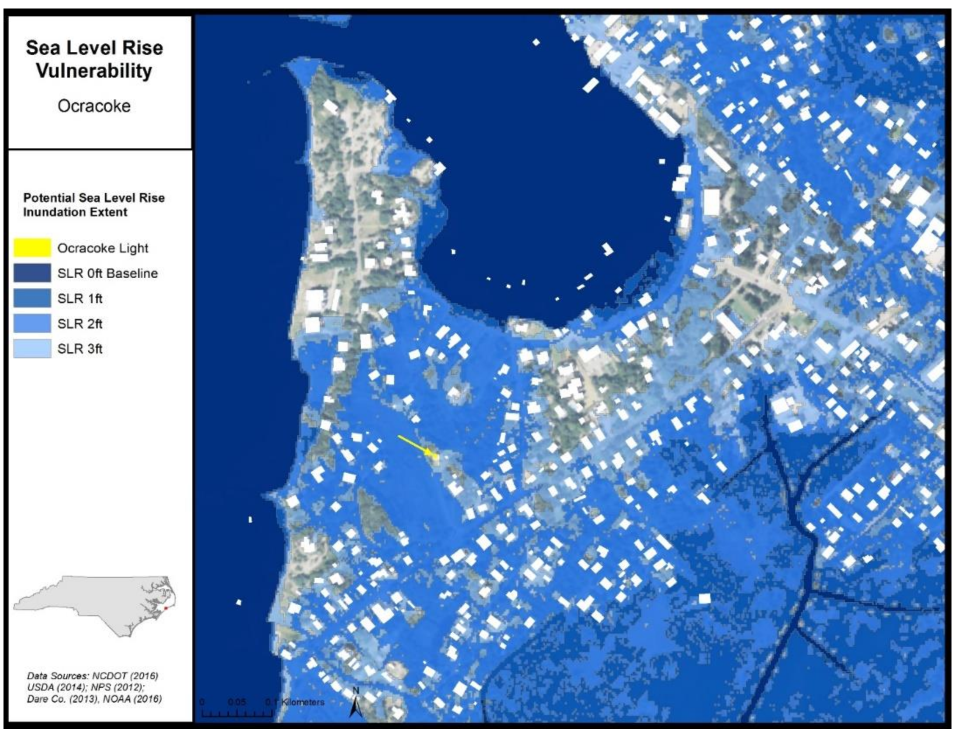


Figure 6. Ocracoke Light area potential SLR inundation models suggest accessibility and surrounding property impacts at 2-3ft rise levels.

3.1.2 Relative Vulnerability

Figures 2-5 depict a consistent portrayal of potential static sea level rise. Although only a first-order estimate that does not account for marsh migration and accretion, landform evolution, or human impacts from alteration of beach, backbarrier, or engineering structures, the maps fundamentally show the elevation-area relationship. Low, backbarrier island areas lacking sediment delivery to marshes or narrow estuarine beaches are vulnerable to marsh erosion and fragmentation, and eventually, regular tidal or wind tide inundation. Concise inferences denoted in each figure caption only partially capture the site and situation context of each historic district and structures within. Bodie Island, for instance, has been known to flood in recent tropical and extratropical storms owing to the large estuarine fetch (Hurricane Irene, in particular.) The 1-2ft inundation grids derived already show the site predisposed to flooding at low levels. As relative sea level reaches 1-2ft, the marshes and adjoining roads surrounding Bodie Island Light will be impacted by frequent recurrent flooding during spring tides. In addition, flooding will occur more regularly even with lower intensity levels of extratropical and tropical storms. Little Kinnakeet is similarly more affected in the proximal areas of the backbarrier marshes and low-lying swales. Some of the adjoining roadway of Hwy 12 becomes affected (barring engineering interventions) as soon as 1-2ft of SLR. By contrast, the Hatteras Lighthouse and historic structures are distant from flooding sources with SLR, themselves sited at elevations above the reach, directly, of rising sea level. Nonetheless, there may be ancillary effects of elevated ground water tables on rainfall runoff affecting the transportation and accessibility of these sites. A focus of future study may explore these relationships to inform planning for these areas. The Hatteras Weather Bureau, while situated in a backbarrier location, is surrounded by various creeks occupying former inlet and beach ridge/spot complexes. These low-lying areas and adjoining streets provide conduits for potential floodwaters to affect access to the Weather Bureau. Finally, Ocracoke Island Lighthouse is also in a moderately vulnerable situation with 2-3ft of sea level rise owing to surrounding parcels' low elevation.

The preceding maps convey first-order estimates of potential SLR inundation, yet they do not capture certain coastal hazards that may be amplified in risk as well as impacts. Storm surges, in particular, will be superimposed upon future sea level rise. Sections 3.2 and 4.0 convey the vulnerability of historic structures to storm surges and combination of surges with future sea level rise, respectively.

3.2 Historical Shoreline Change

Shoreline change can be evaluated across a range of time and space scales, short- to long-term. For example, List et al., (2006) demonstrated how shoreline erosion may be very short-lived. The purpose of the historical shoreline change assessment was to analyze the chronic (long-term) trends associated with cross- and long-shore sediment transport in the study area. Historical shoreline changes reflect the long-term sediment budget of the shore and its net movement, including overall barrier island retreat and other morphodynamics. Shoreline change is critical to not only the direct threat to structures near the beach, but also to transportation including visitor and resident vehicular access and egress. Among the limitations of shoreline change analysis, historical shoreline data do not include vertical elevation changes, and are often mapped using the wet-dry line or wrack baselines, and thus the character of adjoining dunes (dune crest, volume, width) and beach is not assessed (nor is it available for most historical periods prior to LiDAR or aerial orthophotography). Nonetheless, historical shoreline change analysis provides a fundamental measure of the long-term evolution and can induce damage to historic structures (this is why the Cape Hatteras Lighthouse was moved in 1999; c.f., https://www.nps.gov/caha/learn/historyculture/movingthelighthouse.htm).

3.2.1 Methods

Historical shoreline shapefiles were obtained from the NCDCM) for the following years: 1946, 1980, 1997, 1998, 2004, and 2009 (Table 1). The USGS Digital Shoreline Analysis System (DSAS) version 4.3.4730 was used to calculate and display rate-of-change statistics in ArcMap. This involved: (1) constructing a baseline seaward of and parallel to the shorelines that were used in the measurement; (2) generating transects that were spaced 50 m apart; and (3) performing statistical computations in DSAS to produce a linear regression rate (LRR) of shoreline change along each transect as well as determine the shoreline change envelope (SCE) (Figure 7). The LRR rate-of-change statistic is determined by fitting a least-squares regression line to all shoreline points for a particular transect, and the LRR is the slope of the line (Theiler et al., 2009). The SCE is the line segment between the shoreline farthest from and closest to the baseline at each transect. Mapping all segments represents the maximum area of change from shoreline movement for all available shoreline positions regardless of their dates (Theiler et al. 2009). The statistics were calculated with a 90% confidence interval, which means that the true rate of shoreline change falls within the range defined by the reported value plus or minus the error value. The variability around the trend reflects both mapping and measurement errors.

Table 1. Dates, sources, scale and resolution of available oceanfront shoreline data. (NCDCM, Division of Coastal Management vector shorelines). The average shoreline recession rate across the full extent of the seashore oceanfront was 2m/yr using the linear regression rate and USGS Digital Shoreline Analysis System. Table does not include 19th century NOAA charts that were excluded owing to accuracy concerns after exploratory analysis.

Shoreline Date	Source	Scale	Spatial accuracy (mean RMSE m)
1946	NOAA T-sheets	1:10,000	10.8 m
1980	NOAA T-sheets	1:10,000	5.1 m
1997	USGS LiDAR	20m resolution	1.5 m
1998	NCDCM aerial	Not specified	Not specified
2004	NCDCM aerial	Not specified	Not specified
2009	NCDCM aerials (ECU digitized)	1:2,400	4.0 m

Figure 7. Shoreline change measurement techniques employed using USGS DSAS. LRR was used for detailed analysis. Owing to concerns over the accuracy of the oldest t-sheet charts, these 1800s maps were not used to estimate the LRR rate of change. (Summaries adapted from USGS DSAS 6.)

Shoreline Change Envelope (SCE)

SCE is the calculated distance between the closes and farthest baseline along a transect in DSAS. The envelope creates a polygon capture the total area of shoreline change irregardless of date (Thieler et al. 2009)

Net Shoreline Movement (NSM)

Given two shoreline dates, the NSM is the calculated lateral distance moved between oldest and newest shoreline.

End Point Rate (EPR)

EPR is derived by dividing the distance of shoreline change by the time interval between the oldest and newest shorelines. EPR only requires two shorelines and provides a simple computation. However, EPR may ignore changes in shoreline movement through the intervening period (e.g., accelerationg erosion or accretion, or cycles) (Crowell et al. 1997; Dolan et al. 1991.)

Linear Regression Rate (LRR)

Linear regression rate of change is derived by fitting an ordinary least-squares regression line to all shoreline point locations along a transect. LRR is the slope of the line. The method includes all data available (not just oldest-newest as in EPR or NSM), is purely computational, and is easily implemented. The LRR technique is susceptible to error, nonetheless and inhomogeneity of variances. Individual shoreline dates may skew the estimate (detectable with residuals), and the method has a documented tendency to be a conservative estimate of change relative to EPR (Dolan et al. 1991; Genz et al. 2007.)

3.2.2 Regional Results

The results were first analyzed to determine the percentage of transects that exhibited a historical shoreline change rate that was either erosional or accretional. Across the Outer Banks, nearly three quarters of the oceanfront shoreline of the study area exhibited an erosional trend; 72% of transects had a LRR < 0 m/yr. The results were then further subdivided for display purposes on the historical shoreline change maps (Table 2).

Table 2. Percent of transects associated with shoreline rate of change.

Category	Shoreline Change Rates (m/yr)	Percent
Highly Erosional	< -2	22
Moderately Erosional	-2 to -1	22
Relatively Stable	-1 to 1	48
Moderately Accreting	1 to 2	5
Highly Accreting	> 2	4

Several regions within the study area have exhibited long-term ocean shoreline erosion, including: in southern Nags Head, north of Bonner Bridge; portions of Pea Island National Wildlife Refuge including the area north of Rodanthe (locally known as “S – Curves”); much of the Village of Rodanthe; south of Avon until Hatteras Point; the Hatteras Inlet Hazard Area (continues onto Ocracoke Island); and the Ocracoke Inlet Hazard Area (Figure 8).

This shoreline change assessment helped identify erosional hotspots in relation to the location of the historical districts. The historical districts include: Bodie Island Lifesaving and Coast Guard Station, Bodie Island Lighthouse, Little Kinnakeet Main House, Cape Hatteras Lighthouse, Hatteras Island Ranger Station and the Civilian Conservation Corps (CCC) cabins, Hatteras Island Weather Bureau, and Ocracoke Lighthouse. ***All of the historic districts except the Ocracoke Lighthouse are currently located in regions where the long-term oceanfront shoreline has had an erosional trend*** (Figure 9)**.** Linear regression rate (LRR) was chosen as the preferred method for analysis since it is statistically robust, quantitative method when a limited number of shorelines are available. LRR is also commonly applied for expressing shoreline movement and estimating rates of change (Figure 5). Conducting the analysis with more recent shorelines derived from LiDAR should not only give additional temporal and spatial data but also can inform associated morphological changes. It must be recognized that many factors are driving shoreline changes including natural (e.g., storm-driven overwash and longshore transport) as well as anthropogenic activities (e.g., nourishments). To understand past and future changes requires knowledge of beach replenishments, lagged effects from alongshore pulses of erosion updrift, inlet opening and and other processes that modify the sediment budget (Inman and Dolan, 1989). Moreover, the geologic framework and regional-scale morphology may be important in controlling spatial and temporal changes in erosion.

Figure 8. Map of erosion and accretion along the oceanfront shoreline. Long-term average annual erosion rate from DSAS utilizing the most recent 2011 DCM shoreline data. Categories correspond to net long-term shoreline change reported in Table 2. All historic districts are categorize as having net erosional state for nearby oceanfront shorelines.

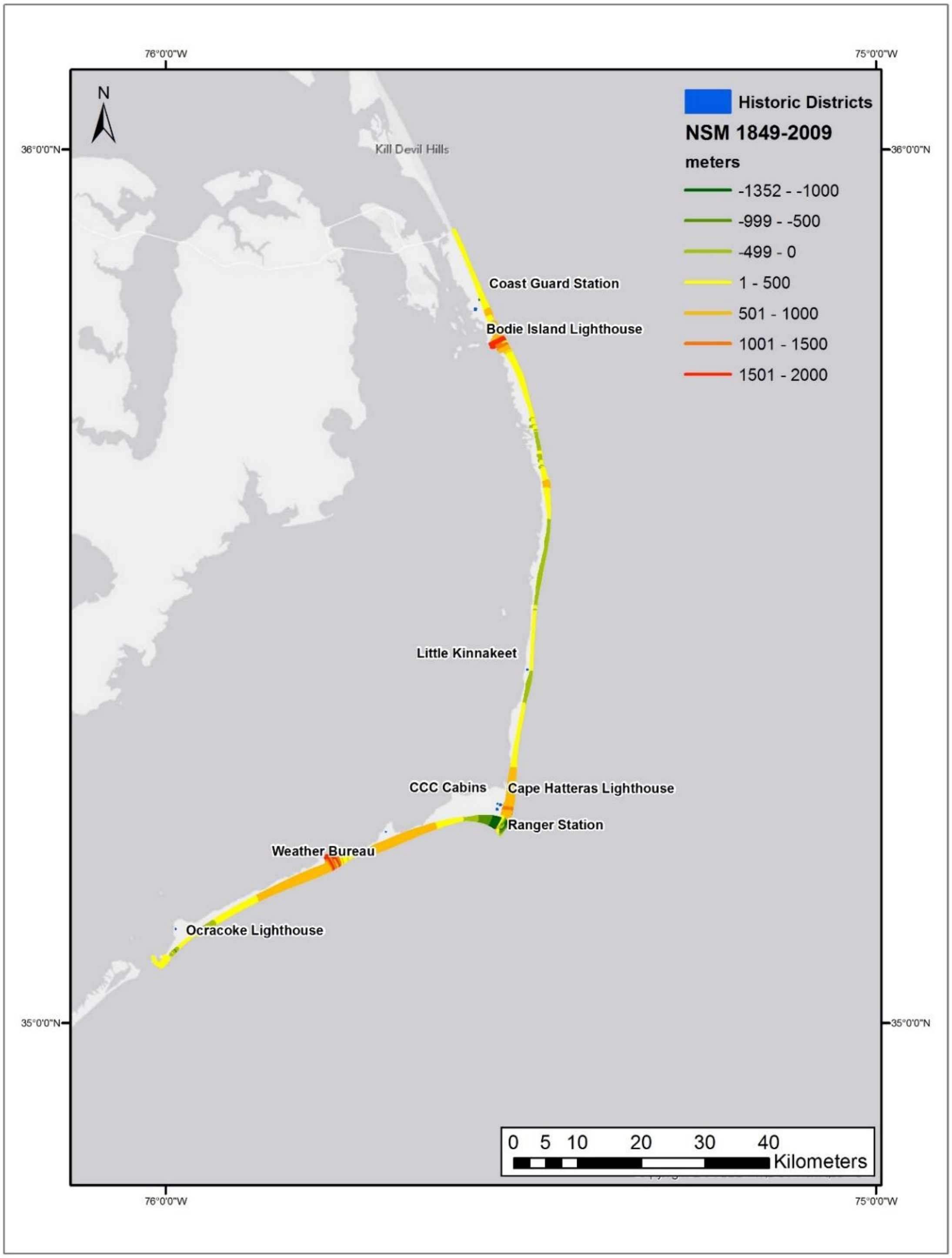


Figure 9. Map of areas where shoreline has moved. NSM was derived from DSAS analysis of shoreline changes 1849-2009. Using the oldest available NOAA charts, the NSM derived shoreline changes corroborate linear and end point regression methods. However, owing to the uncertain spatial accuracy of the oldest 19th century charts, these measurements are provided for relative, comparative purposes only.

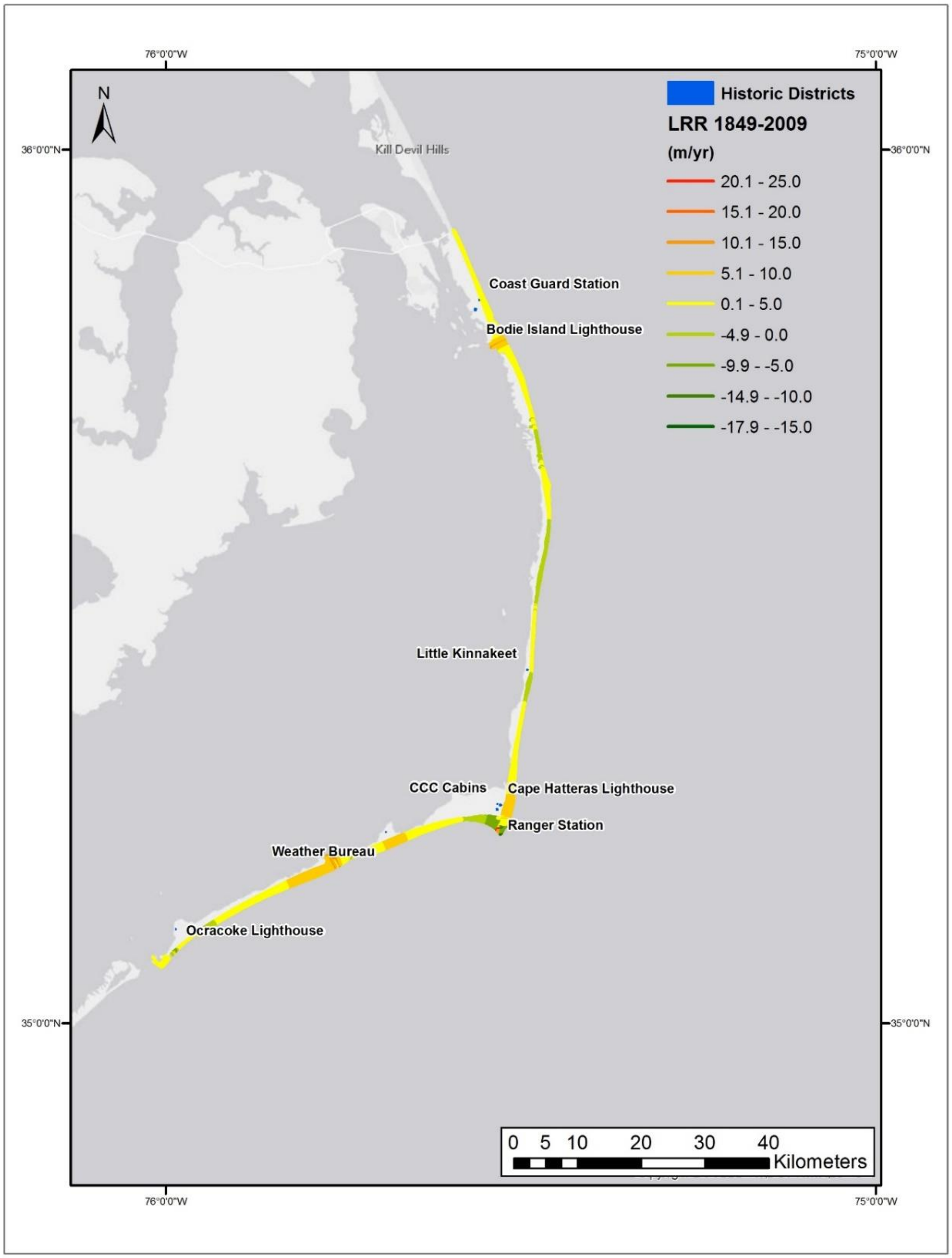


Figure 10. Map of ocean shoreline change rates. Linear Regression Rate of Change (LRR) from 1849 to 2009 calculated for all shorelines for exploratory purposes. Similar to the NSM measurement results, the longest period of record shoreline change also underscores the overall extent of erosional shorelines and context. It is difficult to ascribe precision to individual shoreline rates of change, owing to the positional uncertainty of shorelines in the oldest chart.

3.2.2 Erosion Results and Discussion

Even though the oceanfront shorelines near most of the Historic Districts are exhibiting a long-term erosional trend, the current locations of these structures may still provide adaptive capacity (e.g., relocation or raising freeboard elevation) from sea-level rise. Future studies should consider more detailed, site-specific assessments that also factor in back-barrier estuarine shoreline movement as well as simulated sea-level and storm event scenarios to evaluate coastal vulnerability of these cultural resources. Limitations of this assessment include a paucity of finer temporal scale interannual change data and a purely empirical approach oriented to long-term trends.

Recent storm- and human-cause modifications updrift and localized along Pea Island (e.g., the nourishment north of Rodanthe in 2015), Hatteras, and Ocracoke coastal compartments could impart short- and long-term changes with lag effects in shoreline response. In addition, the stability of Pea Island section of Highway 12 has been recently dependent upon almost continual engineering activity, and policies adopted and actions taken now and over the next decade or two (e.g., bridge construction) could have measurable along-shore consequences for sediment supply and thus shoreline, beach and dune morphology across the study area.

Relative to potential SLR inundation and surges (discussed later) no CAHA sites exhibit a severe, immediate risk to oceanfront erosion. This result certainly includes significant risk reduction resulting from the relocation of the Cape Hatteras Lighthouse and associated quarters. Nonetheless, long-term rates of erosion are predominantly erosional with a high confidence of continued landward recession of the shorezone. Table 3 summarizes the rates and projects these linearly at 10, 25, and 50yr periods in the future from 2009. Figures 11-13 also depict the spatial proximity of each historic site to the oceanfront. Although no sites are directly impacted by shoreline erosion within these periods, the CG site at Bodie Island and the Ranger site at Cape Hatteras show the greatest increase in risk owing to oceanfront erosion. As the shoreline approaches these structures, other chronic and nuisance impacts may be expected to concomitantly increase (e.g., salt spray and wind) as windward landforms and vegetation degrade.

Table 3. Summary of long-term oceanfront erosion rates and recession for selected historic sites. Distance to Oceanfront Shoreline (DOS) is shown with observed historic rates (linear regression rates [LRR] 1946-2009) extrapolated future. Net Shoreline Movement (NSM) and end-point regression (EPR) are included for comparison.

Site	LRR Mean (m/yr)	LRR Std. Dev. (m/yr)	NSM (m)	EPR Mean (m/yr)	DOS (m)	DOS 10yrs (m)	DOS 25yrs (m)	DOS 50yrs (m)
BI CG Site	-2.88	0.08	-182.23	-3.01	288	259	216	144
BI Lighthouse	-2.73	0.2	-165.84	-2.74	1136	1108	1067	999
HI Little Kinnakeet	-0.86	0.12	-47.75	-0.75	487	478	465	444
HI Lighthouse	-3.23	0.43	-207.94	-3.27	467	434	386	305
HI Ranger	-3.69	0.11	-214.57	-3.38	820	783	728	636
HI CCC Cabins	-3.23	0.43	-207.94	-3.27	896	864	815	735

Since the Hatteras Weather Bureau and Ocracoke Island occupy backbarrier and sheltered locations, these sites were not analyzed for proximity to oceanfront erosion risk, which is extremely low through the period of study.

Figure 11. Map of oceanfront shoreline change rates at the Bodie Island area of interest. Linear Regression Rate of Change (LRR) from 1946 t0 2009. Distance to Oceanfront Shoreline (DOS) was measured and tabulated using projected LRR rates in Table 3. A net erosional state exists for the oceanfront in this vicinity. Soundside estuarine erosion rates may merit further study for the Bodie Island Lighthouse site.

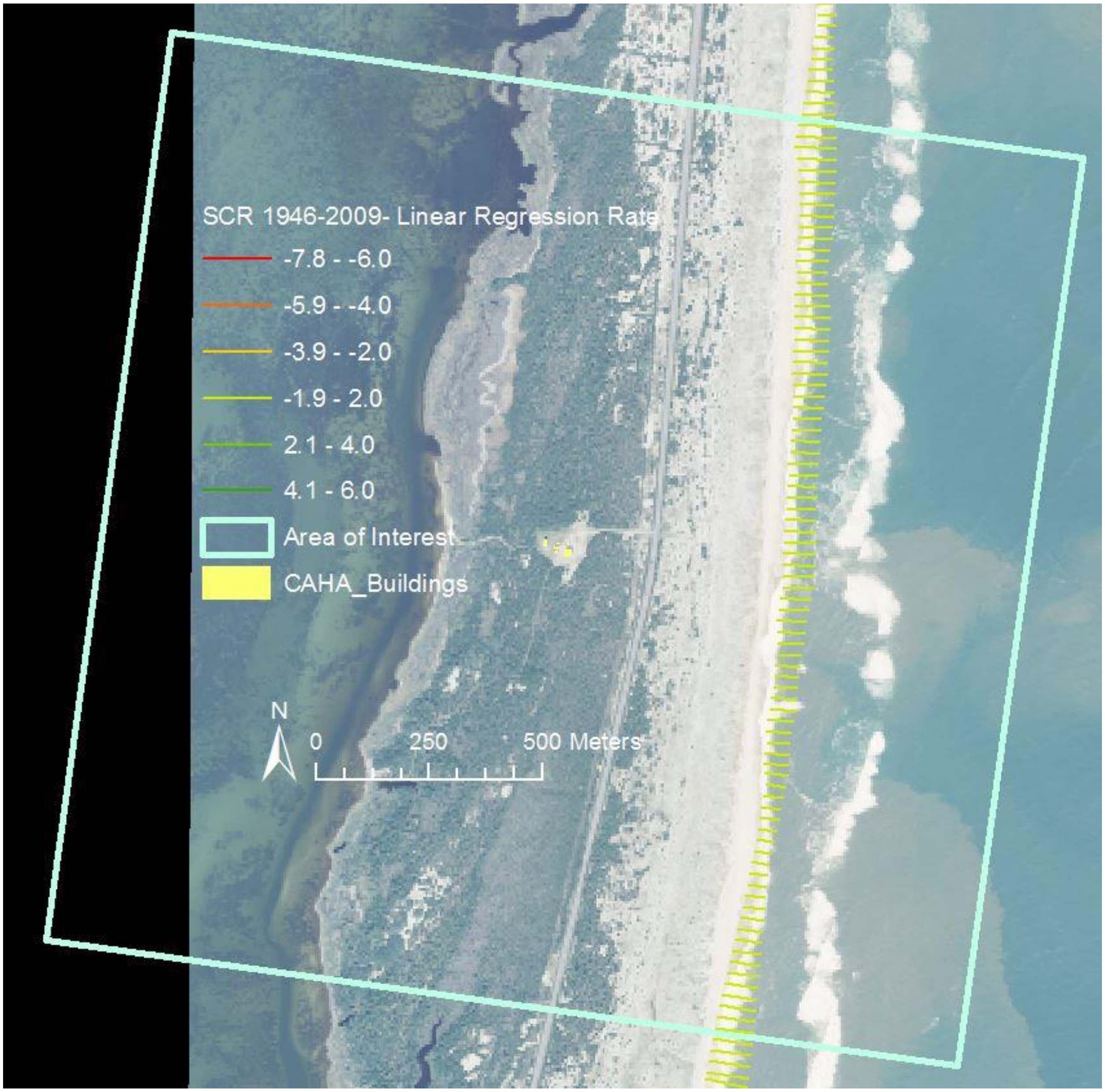


Figure 12. Map of oceanfront shoreline change rates at the Little Kinnakeet area of interest. Linear Regression Rate of Change (LRR) from 1946 to 2009. Distance to Oceanfront Shoreline (DOS) was measured and tabulated using projected LRR rates in Table 3. Kinnakeet exhibits a lower rate of shoreline erosion than Bodie Island, yet backbarrier estuarine shoreline change merits consideration.

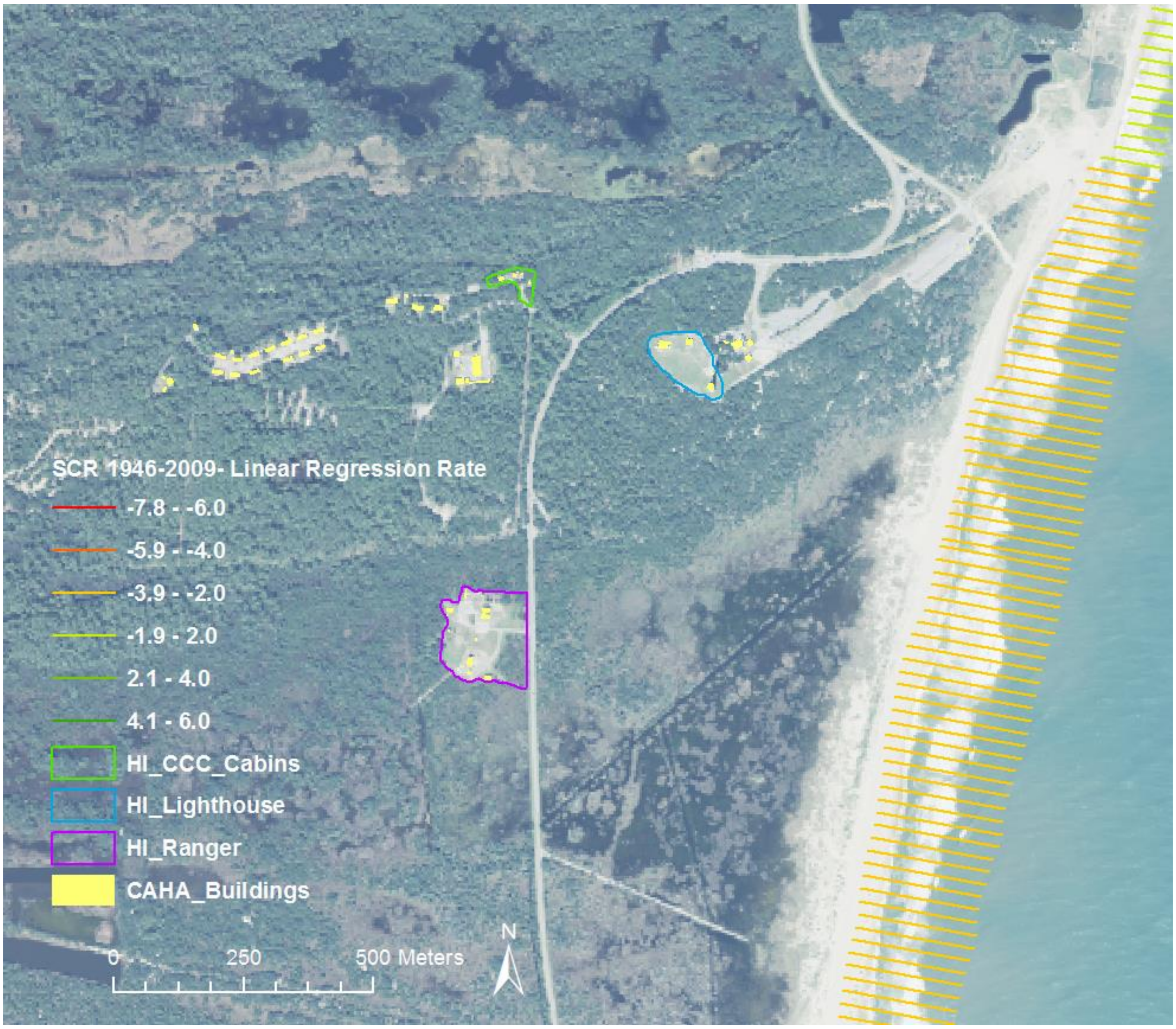


Figure 13. Map of oceanfront shoreline change rates at the Cape Hatteras area of interest. Linear Regression Rate of Change (LRR) from 1946 to 2009. Distance to Oceanfront Shoreline (DOS) was measured and tabulated using projected LRR rates in Table 3. Relative risk is obviously reduced since the relocation of the lighthouse and associated quarters. While sited well away from the shoreline, the high historic rate of erosion at the site remains a consideration for future landform change. Low swales and ponds scattered at the cape may also exacerbate nuisance heavy rainfall and groundwater-induced ponding.

3.3 Storm Surge Vulnerability

The storm surge vulnerability assessment combined downscaled storm surge simulation modeling and future sea level rise to evaluate the susceptibility of historic structures to storm impacts today and under future sea level states. The adopted methodology incorporates techniques adapted from the NOAA Storm Surge Inundation Mapping guide, NC SLRRMS, and several projects conducted at East Carolina University. The principal data include: 1) the newest NOAA National Hurricane Center (NHC) Sea, Lake, and Overland Surges from Hurricanes (SLOSH) basin models; 2) Historic Districts and specific historic structure building footprints; and 3) associated shoreline and basemap information. Spatial analysis included co-registration in the horizontal (e.g., UTM earth coordinates) as well as adoption of a common vertical datum for all data (DEMs, buildings, and surges.)

Storm surge modeling data was obtained from the SLOSH display program and used to map the extent and depth of inundation resulting from various storm scenarios (Figure 6). The SLOSH model was developed by the National Weather Service's NHC to estimate storm surge from hurricanes using storm properties (e.g., track speed and direction, central pressure, and radius of maximum winds) (National Hurricane Center, 2015). The newest available SLOSH grids for the Hatteras area were obtained and co-registered to the NC LiDAR, building footprints, and other GIS datasets.

We conducted a search and review of available building footprints and elevation data, including the NPS GIS databases, NC Floodplain Mapping Program, and the Dare County GIS. In 2009, the North Carolina Flood Mapping Program conducted a statewide acquisition of building footprints based on orthophotography to develop a statewide GIS layer for the purpose of vulnerability assessment, disaster mitigation, planning and flood forecasting. This effort included a program to collect first (or finished) floor elevation (FFE) data using mobile LiDAR and laser inclinometers in order to refine flood hazard assessments to the building footprint scale (NCFMP 2014). The FFE is a useful threshold to identify individual properties that are vulnerable to flooding because if the flood depth exceeds the FFE of a property, the owner may have to remediate interior and exterior damages. If the damage is severe, the property may become unusable, at least temporarily. FFE measurements were collected using various techniques under contract for NC Floodplain Mapping and FEMA (e.g., direct survey using leveling and RTK-GPS, mobile LiDAR measurement, measured and/or statistically estimated FFE above adjacent highest grades, and in some instances, measurement from the high density airborne QL2 LiDAR point clouds). NCFMP FFE data were adopted for the purpose of analysis. These data also have the benefit of well documented lineage, completeness, and currency as compared to the incomplete data sources from Dare County and NPS building data (methods undocumented, buildings incomplete, and some missing.) The objective this effort was to collect data on building elevations to analyze susceptibility to surge and SLR impacts.

3.3.1 Methods

There are three modeling approaches that can be used to estimate storm surge: the deterministic, probabilistic, or the composite (NHC 2016). The deterministic approach performs a single simulation based on a hurricane forecast. The probabilistic approach, for example P-Surge, performs ensemble model runs based on forecast error. The composite approach actually has two variants, the Maximum Envelope of Water (MEOW) and the Maximum of the MEOWs (MOMs), "which are regarded by the NHC as the best approach for determining storm surge vulnerability for an area since it takes into account forecast uncertainty" (National Hurricane Center, 2015). In other words, MEOW and MOM simulations allow for uncertainty in forecast tracks and landfall. These output allow for a wider regional assessment of a given scenario of a hurricane category, rather than using a single track or historical scenario which would focus impacts at local scales. The SLOSH MEOWs are a composite product that is produced from thousands of model runs with the same category, forward speed, storm trajectory, and initial tide level. The track of each model run is shifted some distance to the right or left of the main track to account for uncertainty and the maximum value that is calculated for a particular grid cell is assigned (NHC 2016). The SLOSH MOMs provide a worst case scenario product as they are compiled based on the maximum storm surge height for all hurricanes of a given category regardless of forward speed, storm trajectory, or landfall location. Since the purpose of this assessment was to identify the vulnerability of the region to storm surge, and previous studies (Barnes, J., 2013; Clinch et al., 2012; Mulligan et al., 2014; Riggs, 2011; Sheng et al., 2010) illustrated the variability of storm surge as well as the geomorphic response to different storm events, the scenarios selected included the (MOMs) for Category 1 – 5 storms occurring at high tide in order to identify the development that is the most vulnerable and use a worst case scenario to assist with prioritizing mitigation actions (Allen et al., 2013).

Accurate and recent topographic and bathymetric data is a critical component to mapping potential inundation caused by storm surge. Fortunately, the National Oceanic Atmospheric Administration's National Geodetic Survey Remote Sensing Division collected Quality Level 2 LiDAR data in 2014 for the North Carolina Floodplain Mapping program using a Riegl VQ820G system. The bare earth LiDAR that was produced from that mission was obtained through the North Carolina Emergency Management Spatial Data Download portal (rmp.nc.gov/sdd/) for the extent of the study area as individual tiles containing LAS files (an industry standard binary format for storing LiDAR data). LAS Dataset (Data Management) in ArcGIS 10.2 was used to create a mosaic all the tiles covering the study area. LAS Dataset to Raster was then used to create an elevation surface. The QL2 LiDAR had a point spacing of approximately 2 points per meter with a horizontal accuracy of 1.0 m root-mean-square error (RMSE) and vertical accuracy of 0.245 m RMSEz. These data allowed for the creation of a 1.5 meter resolution DEM using Natural Neighbor interpolation as the void filling method. A polygon delineating areas of water for the region was obtained through the National Hydrography Dataset and used to clip the extent of the DEM from the 2014 QL2 bare earth LiDAR. The resultant DEM was then used for the storm surge inundation mapping.

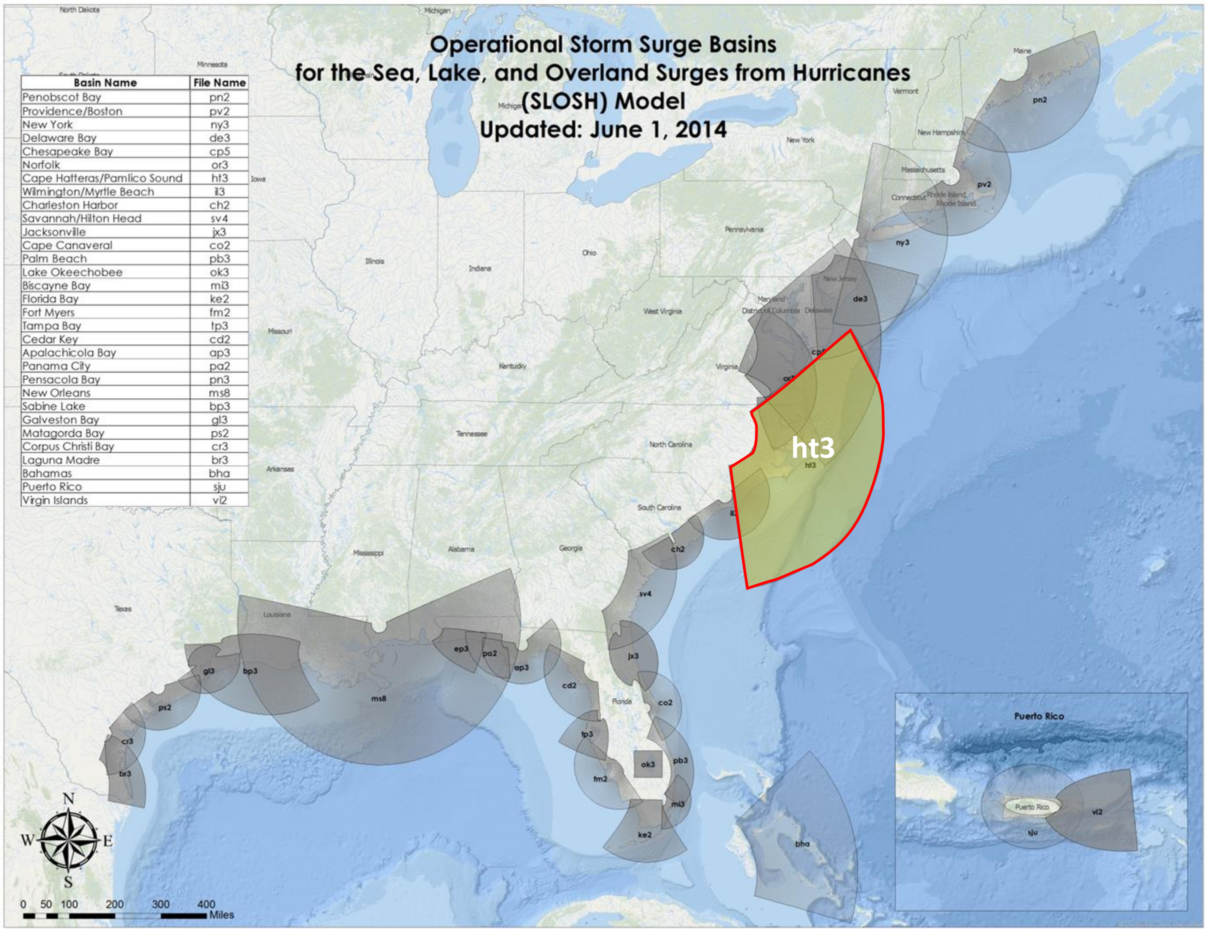


Figure 14. SLOSH basin zones. The latest available Cape Hatteras-Pamlico Sound SLOSH model basin (ht3, highlighted) was used for creation of Maximum of Maximum (MOMs) induction models, subsequently downscaled to LiDAR DEMs for inundation mapping. Figure adapted from NOAA NHC.

3.2.3 Surrounding Community Vulnerability

Mapping the storm surge inundation involved exporting the data from the SLOSH display program that contained the height of the storm surge that was modeled using the MOMs approach for the Cape Hatteras/Pamlico Sound (ht3) Basin for each category storm that occurred during high tide (Figure 7). The SLOSH display program exports the data as a shapefile in WGS84. The shapefile was then projected into the UTM Zone 18 North (meters) coordinate system, and the polygons were then converted to points containing the water level values. Additional fields were added to each attribute table, and the appropriate value was added to the SLOSH output to simulate the height of the storm surge that would occur under different sea level rise scenarios of 20, 40, 70, 100, and 140 cm. The Spline interpolation method was used to create a water surface based on the SLOSH point attributes at a 5-m resolution. The interpolated surface was then subtracted from the DEM using Raster Calculator. Raster Calculator was then used to create a raster of inundated areas containing values representing the depth of inundation in each cell (also known as a “depth grid.”) This inundation mapping was completed for the entire CAHA study area and provide a baseline (along with the NOAA SLR Viewer and section 3.1) for potential exploration of adaptation and relocation strategies.

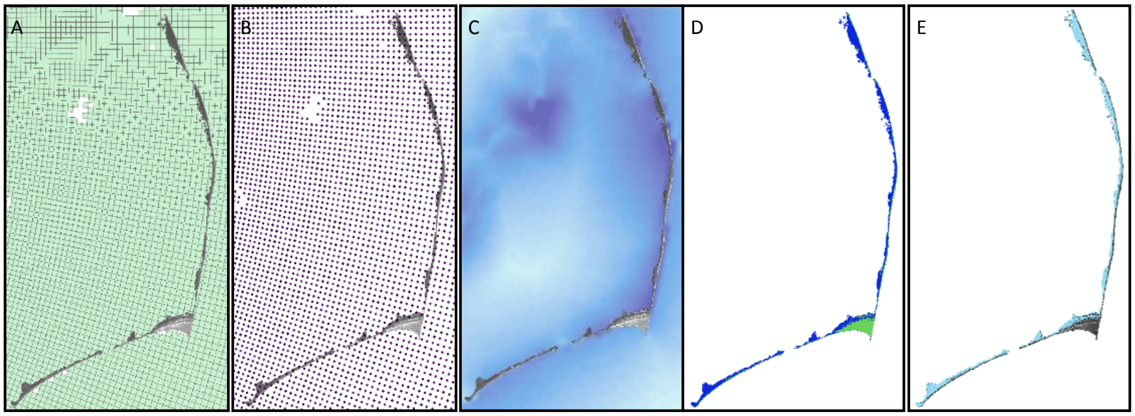


Figure 15. The storm surge inundation mapping process. (A) Project SLOSH MOM polygon (B) Convert SLOSH polygon to points (C) Interpolate water surface (D) Subtract DEM from the inundation surface to develop flood depth grid (E) Create an inundation extent polygon.

Dare County and Hyde County Building Footprint data were obtained from the North Carolina Floodplain Mapping Program and imported into ArcGIS 10.2. A separate building footprint layer was created for the study area by selecting the polygons that were located within the study area polygon. The following protocol was performed in order to determine if the water level of each flood depth grid exceeded the FFE of each individual building footprint.

- The *Feature to Point* tool was used to create centroids of all the building footprints.
- The *Extract Multi Values to Points* tool was used to extract the value of each flood depth grid at point locations and append the values to the attribute table of the building centroids.
- Additional fields were added to the attribute table and populated using *Field Calculator* to determine the difference between the FFE and the flood depth.
- *Select by Attribute* was used to determine the number of buildings that were inundated in each surge scenario based on different threshold levels (Table 5).
- In order to map the results, the table of the building centroids used a *Join* operation to link the building footprint data attributes to points based on a unique identifier (Building ID) for map symbolization.

Analysis of each community provides context on how different scale events may impact the functioning of the area (and thus impact park visitation). Interestingly, , the development located in Rodanthe, Waves, and Salvo (also known as the "Tri-Villages") was not very vulnerable to a category 1 hurricane, only 4%, 5%, and 2% of the property within the respective communities had the potential to be inundated. However, the percentage of properties in the Tri-Villages that has the potential to be inundated jumps to over 30% for a category 2 hurricane. In contrast, the results for Ocracoke indicate that 12% of the properties are vulnerable to a category 1 hurricane, however, the percentage is drastically greater (57%) for a category 2 hurricane, the highest for all the communities. Finally, storm surge inundation produced from category 3-5 hurricanes has the potential to be severe for the entire region as the percent of properties vulnerable to inundation is greater than 47% for all of the communities.

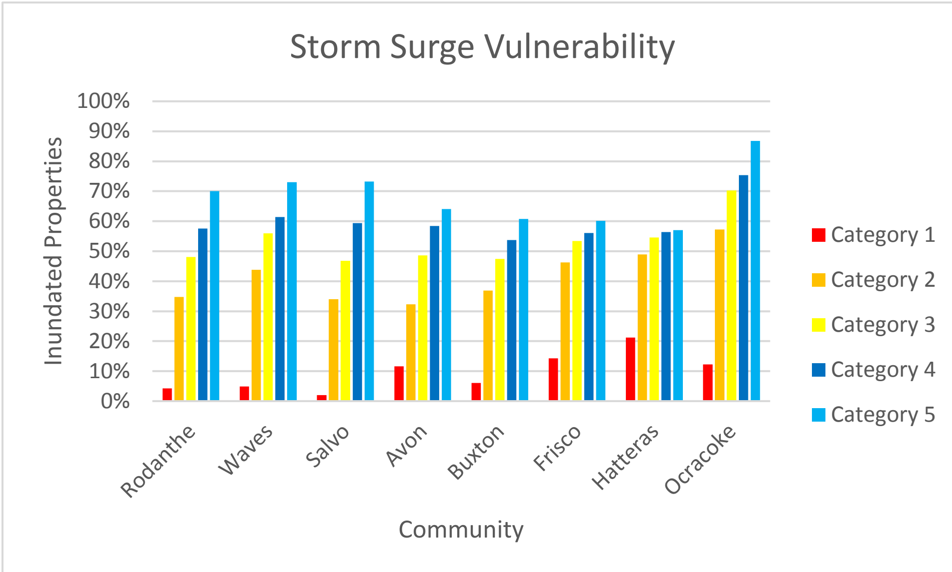


Figure 16. Bar graph of percentage of inundated properties by community. Storm surge vulnerability assessment results are presented as the percent of properties that could be potentially inundated from Category 1 – 5 hurricane events within each community by determining if the inundation exceeded building FFE.

Table 4. Storm surge community vulnerability results. Data presented are the number of properties that estimated to be inundated from Safir-Simpson Category 1 – 5 hurricane MOM inundation event simulations within each community by determining if the inundation exceeded the FFE.

Community	Buildings	Category 1	Category 2	Category 3	Category 4	Category 5
Rodanthe	618	26	215	297	356	433
Waves	516	25	226	289	317	377
Salvo	815	16	277	381	484	597
Avon	1915	222	619	931	1118	1226
Buxton	1525	93	563	723	820	926
Frisco	1531	219	708	817	858	921
Hatteras	1145	243	560	625	646	653
Ocracoke	1340	164	767	942	1010	1163
Total	9405	1008	3935	5005	5609	6296
Percent		11%	42%	53%	60%	67%

The results of the storm surge mapping were first analyzed by the potential extent of inundation that could occur from the different category storm events as well as under different sea level rise scenarios. Based on the Storm Surge Vulnerability maps that displayed the potential extent of inundation (see appendices) it was determined that the region of the barrier island located adjacent to the Pamlico Sound is quite vulnerable to inundation beginning with a category 1 hurricane, as Hurricane Irene (2011) demonstrated (Mulligan et al., 2014). The extent of potential inundation increases considerably between a category 1 and category 2 event, while the areas of potential inundation from a category 3 – 5 event increase less drastically. In general, areas with an elevation of 3 meters (NAVD88) or above are the only areas that do not have the potential to be inundated by any category hurricane. Section 4 further examines whether this pattern persists with increasingly sea-level and specifically within NPS historic districts.

The results of the storm surge community vulnerability assessment using the FFE of the building footprints affirm the wide extent of potential inundation. While 11% of the coastal development has the potential to be inundated by a category 1 hurricane, the number of properties that have the potential to be inundated by a category 2 hurricane is 42%, an increase of 31%. An additional 11% of properties have the potential to be inundated by a category 3 hurricane (i.e., 53%). Subsequently, an increase of 6% (59%) and 7% of structures was determined to be inundated by category 4 and 5 hurricanes, respectively. The results of the storm surge vulnerability assessment using the FFE of the building footprints illustrate that there is significant spatial variability in the vulnerability of properties; whereas the maps that display the potential extent of inundation are directly correlated with elevation. (Detailed district-level interpretive analyses for CAHA structures follows and include composite susceptibility when storm surges are superimposed on SLR, detailed in section 4).

3.2.3 Regional CAHA Surge Vulnerability

The results of the sea level rise scenarios illustrate that **as sea level rises the magnitude of the hurricane required to generate a similar extent of inundation decreases in comparison to the results from the inundation that was mapped with baseline sea level**. The effect of the addition of sea level rise is logical and expected, but it is useful to evaluate over areas with low gradients and display for planning purposes. Our intent to process inundation models, surge grids and erosion rates across the extent of CAHA would incur substantial computational effort but also help identify potential areas suitable for the relocation of buildings and infrastructure and analysis of the surrounding communities in subsequent studies.

Figures 15 and 16 illustrate the regional context of CAHA historic districts in relation to storm surges and future sea level rise. Across much of the region today, a category 2 storm surge of a nearby landfalling hurricane is required to inundation most areas of the Outer Banks in our modeling with SLOSH and LiDAR DEMs. In the future, even at +20cm SLR there is evident expansion of areas vulnerable to flooding by category one and two storms. However, this scale of analysis does not allow the assessment of individual buildings. These figures, it should be noted, are cartographically coarse-scale, yet the modeling was conducted at finer resolution. Section 4 covers the results and discussion for CAHA historic districts and structures.

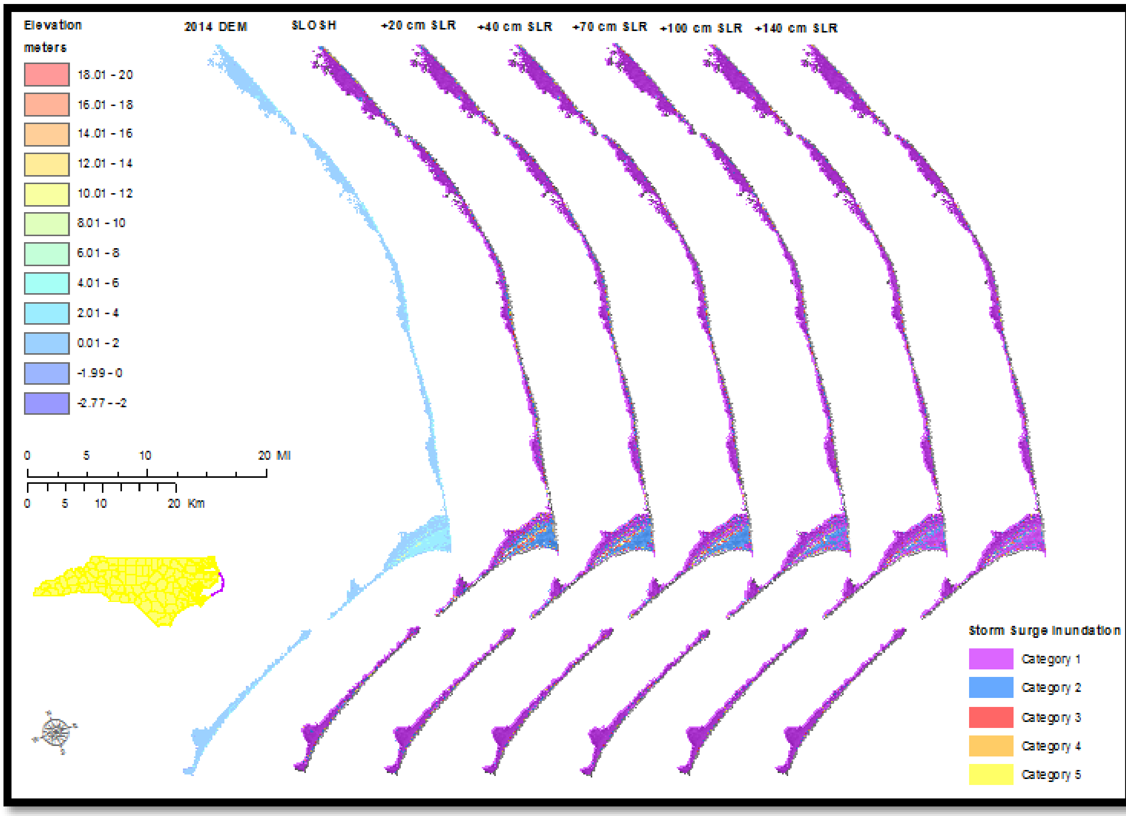


Figure 16. Regional Storm surge inundation extent for downscaled SLOSH MOMs under various relative SLR scenarios.

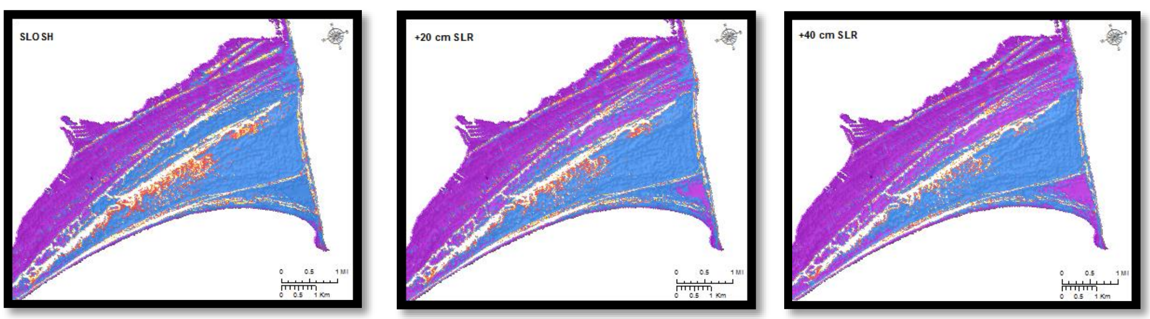
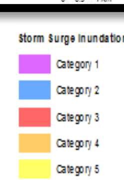


Figure 17. Zoom view of SLOSH-SLR inundation mapping for Cape Hatteras area for baseline sea level, +20cm, and +40cm SLR.



4. SEA LEVEL RISE AND STORM SURGE

This section presents results of site level vulnerability assessment, focusing on the historic structures and landmarks for each district and their elevation relationship between finished first floors (FFE) and the height of SLOSH storm surge models *with* sea level rise. Figure 18 portrays some of the underlying data, a SLOSH inundation grid superimposed on the LiDAR DEM with building centroids and footprints (inset A and B). Each building footprint and associated centroid is elevationally compared to the surge SLOSH surge category 1-4 height and the offset calculated. Structures where the surge exceeds the FFE are shown as negatives in tables 5-10. These tables provide the reference for ascertaining individual structure potential susceptibility to storm surge impact. Columns reference the SLOSH Safir-Simpson categories, and each table represents a distinct SLR scenario. The contemporary (baseline) Table 6 can then be compared to increasing risk with SLR, as in tables 6-10. Each cell of the table is color-coded to generalized categories of risk for relative comparison among surges and structures, yet consistency with time. Generally, each table portrays increasing risk, since SLR will raise the surge heights and potential impacts to structures.

The following the map and tabular presentation graphics, individual district risk and overall risk are summarized in section 4.1.

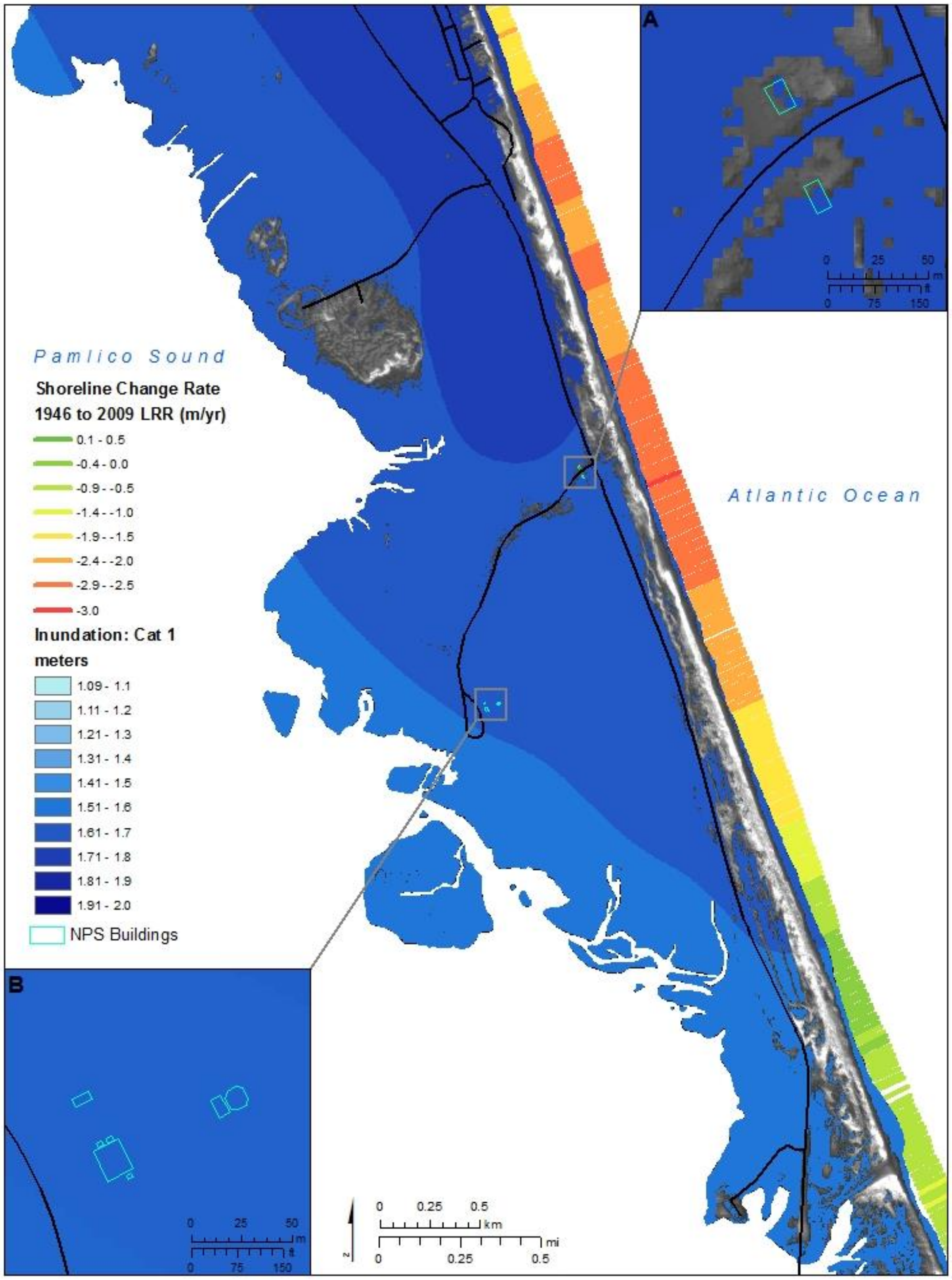


Figure 18. Composite vulnerability for Bodie Island district. Building centroids (main map) and footprints (inset A and B) are mapped at fine-scale for the historic districts. Values at building adjacent grade level heights (lowest and highest) are compared against building first floor elevations (FFE) to determine susceptibility to inundation. Inset maps identify building footprint extent with respect to inundation and elevation (if shown, greyscale reflects elevations above the static surge extent.) Risk maps also include shoreline change rates in proximity to structures from historic shoreline data. Tables 6-11 summarize these FFE susceptibility and scale them using color-coding for five SLR scenarios.

Table 5. Present vulnerability of storm surge for CAHA sites and structures. Data are presented for each feature: First Floor Elevation (FFE), Lowest Adjacent Grade (LAG), Highest Adjacent Grade (HAG), and Digital Elevation Model (DEM) heights. The difference between FFE and SLOSH inundation for each surge category (c1-c5) is given. Positive values indicate no flooding (green). Slight inundation risk (yellow) indicates surge reaching 0-0.5 m above FFE; moderate inundation risk (orange) is flooding of 0.5-1.0 m, and severe inundation risk (red) is >1.0 m of flooding. Features listed by district denoted by two letters in the first column: Bodie Island (BI), Hatteras Island (HI), Ocracoke Island (OI), CG = Coast Guard; LS&RS = Life Saving & Ranger Station; BILS = Bodie Island Light Station; LH = Lighthouse; KQ= Keepers Quarters; LK = Little Kinnakeet; HWB = Hatteras Weather Bureau.

CAHA Sites & Structures	FFE (m)	LAG (m)	HAG (m)	DEM (m)	FFE - c1 (m)	FFE - c2 (m)	FEE -c3 (m)	FFE - c4 (m)	FFE - c5 (m)
BI HS CG Station (Hilton)	2.59	1.17	1.86	1.68	0.90	-0.14	-0.73	-1.10	-1.48
BI HS LS&RS	2.19	1.18	1.46	1.67	0.50	-0.54	-1.14	-1.51	-1.90
BI HS BILS Oil House	0.00	0.00	0.00	0.78	-1.61	-2.61	-3.30	-3.74	-4.25
BI HS BILS Cistern North A	0.00	0.00	0.00	0.85	-1.61	-2.61	-3.30	-3.74	-4.24
BI HS BILS Cistern North B	0.00	0.00	0.00	0.89	-1.61	-2.61	-3.30	-3.74	-4.24
BI HS BILS Cistern South	0.00	0.00	0.00	0.93	-1.61	-2.61	-3.30	-3.74	-4.24
BI HS BILS LH	1.58	0.64	0.85	0.78	-0.03	-1.03	-1.72	-2.16	-2.67
BI HS LH Store House	1.77	0.92	1.04	0.87	0.16	-0.84	-1.52	-1.96	-2.46
BI HS KQ & Visitors Center	2.00	0.81	1.26	0.94	0.39	-0.61	-1.30	-1.74	-2.25
HI HS LK Main House	4.65	1.36	1.59	1.48	3.00	1.95	1.05	0.59	0.29
HI HS LK Boathouse	1.92	0.88	1.19	1.50	0.27	-0.78	-1.68	-2.14	-2.44
HI HS LK Kitchen	1.83	0.85	1.10	1.25	0.18	-0.88	-1.78	-2.24	-2.54
HI HS CCC Cabin 321	7.52	6.54	6.79	6.70	7.52	7.52	7.52	7.52	7.52
HI HS CCC Cabin 322	9.00	8.01	8.27	8.16	9.00	9.00	9.00	9.00	9.00
HI HS CCC Cabin 323	9.32	8.08	8.59	8.26	9.32	9.32	9.32	9.32	9.32
HI HS CCC Cabin 324	0.00	0.00	0.00	7.99	0.00	0.00	0.00	0.00	0.00
HI HS CAHA LH	5.05	2.85	3.15	3.09	5.05	5.05	1.92	1.59	1.23
HI HS CAHA LH Oilhouse	3.42	2.58	2.69	2.92	3.42	0.53	0.29	-0.03	-0.39
HI HS CAHA Principal KQ	3.43	2.48	3.22	2.86	3.43	0.53	0.30	-0.02	-0.38
HI HS CAHA Double KQ	3.68	2.49	3.16	3.15	3.68	0.77	0.54	0.23	-0.13
HI HS CG & Ranger Station	3.64	2.43	2.51	2.67	3.64	0.70	0.50	0.20	-0.14
HI HS CG Equipment Shed	3.76	2.28	3.48	2.43	3.76	0.82	0.62	0.31	-0.02
HI HS HWB	2.61	0.60	0.82	0.90	1.10	0.37	-0.15	-0.38	-0.52
HI HS HWB Shed 1	1.54	0.62	0.81	0.74	0.03	-0.69	-1.21	-1.45	-1.59
HI HS HWB Flag House	1.34	0.48	0.60	0.80	-0.18	-0.90	-1.42	-1.66	-1.79
OI BD Oil House	0.00	0.00	0.00	1.13	-1.30	-1.82	-2.15	-2.54	-3.24
OI HS Ocracoke LH	1.76	0.94	1.02	1.39	1.76	-0.06	-0.39	-0.78	-1.48
OI HS Keepers Quarters	1.79	0.62	1.06	0.94	0.49	-0.03	-0.36	-0.76	-1.46
OI HS Tool House	1.86	0.90	1.13	1.03	0.57	0.05	-0.28	-0.68	-1.38
OI HS Privy	0.00	0.00	0.00	1.14	-1.30	-1.82	-2.15	-2.54	-3.24

Table 6. Present-day-plus-20 cm-sea-level-rise vulnerability estimates of storm-surge flooding for CAHA sites and structures.

CAHA Sites & Structures	FFE (m)	LAG (m)	HAG (m)	DEM (m)	FFE - c1 (m)	FFE - c2 (m)	FEE -c3 (m)	FFE - c4 (m)	FFE - c5 (m)
BI HS CG Station (Hilton)	2.59	1.17	1.86	1.68	0.70	-0.34	-0.93	-1.30	-1.68
BI HS LS&RS	2.19	1.18	1.46	1.67	0.30	-0.74	-1.34	-1.71	-2.10
BI HS BILS Oil House	0.00	0.00	0.00	0.78	-1.81	-2.81	-3.50	-3.94	-4.45
BI HS BILS Cistern North A	0.00	0.00	0.00	0.85	-1.81	-2.81	-3.50	-3.94	-4.44
BI HS BILS Cistern North B	0.00	0.00	0.00	0.89	-1.81	-2.81	-3.50	-3.94	-4.44
BI HS BILS Cistern South	0.00	0.00	0.00	0.93	-1.81	-2.81	-3.50	-3.94	-4.44
BI HS BILS LH	1.58	0.64	0.85	0.78	-0.23	-1.23	-1.92	-2.36	-2.87
BI HS LH Store House	1.77	0.92	1.04	0.87	-0.04	-1.04	-1.72	-2.16	-2.66
BI HS KQ & Visitors Center	2.00	0.81	1.26	0.94	0.19	-0.81	-1.50	-1.94	-2.45
HI HS LK Main House	4.65	1.36	1.59	1.48	2.80	1.75	0.85	0.39	0.09
HI HS LK Boathouse	1.92	0.88	1.19	1.50	0.07	-0.98	-1.88	-2.34	-2.64
HI HS LK Kitchen	1.83	0.85	1.10	1.25	-0.02	-1.08	-1.98	-2.44	-2.74
HI HS CCC Cabin 321	7.52	6.54	6.79	6.70	7.32	7.32	7.32	7.32	7.32
HI HS CCC Cabin 322	9.00	8.01	8.27	8.16	8.80	8.80	8.80	8.80	8.80
HI HS CCC Cabin 323	9.32	8.08	8.59	8.26	9.12	9.12	9.12	9.12	9.12
HI HS CCC Cabin 324	0.00	0.00	0.00	7.99	-0.20	-0.20	-0.20	-0.20	-0.20
HI HS CAHA LH	5.05	2.85	3.15	3.09	4.85	4.85	1.72	1.39	1.03
HI HS CAHA LH Oilhouse	3.42	2.58	2.69	2.92	3.22	0.33	0.09	-0.23	-0.59
HI HS CAHA Principal KQ	3.43	2.48	3.22	2.86	3.23	0.33	0.10	-0.22	-0.58
HI HS CAHA Double KQ	3.68	2.49	3.16	3.15	3.48	0.57	0.34	0.03	-0.33
HI HS CG & Ranger Station	3.64	2.43	2.51	2.67	3.44	0.50	0.30	0.00	-0.34
HI HS CG Equipment Shed	3.76	2.28	3.48	2.43	3.56	0.62	0.42	0.11	-0.22
HI HS HWB	2.61	0.60	0.82	0.90	0.90	0.17	-0.35	-0.58	-0.72
HI HS HWB Shed 1	1.54	0.62	0.81	0.74	-0.17	-0.89	-1.41	-1.65	-1.79
HI HS HWB Flag House	1.34	0.48	0.60	0.80	-0.38	-1.10	-1.62	-1.86	-1.99
OI BD Oil House	0.00	0.00	0.00	1.13	-1.50	-2.02	-2.35	-2.74	-3.44
OI HS Ocracoke LH	1.76	0.94	1.02	1.39	1.56	-0.26	-0.59	-0.98	-1.68
OI HS Keepers Quarters	1.79	0.62	1.06	0.94	0.29	-0.23	-0.56	-0.96	-1.66
OI HS Tool House	1.86	0.90	1.13	1.03	0.37	-0.15	-0.48	-0.88	-1.58
OI HS Privy	0.00	0.00	0.00	1.14	-1.50	-2.02	-2.35	-2.74	-3.44

Table 7. Present-day-plus-40-cm-sea-level-rise vulnerability estimates of storm-surge flooding for CAHA sites and structures.

CAHA Sites & Structures	FFE (m)	LAG (m)	HAG (m)	DEM (m)	FFE - c1 (m)	FFE - c2 (m)	FEE -c3 (m)	FFE - c4 (m)	FFE - c5 (m)
BI HS CG Station (Hilton)	2.59	1.17	1.86	1.68	0.50	-0.54	-1.13	-1.50	-1.88
BI HS LS&RS	2.19	1.18	1.46	1.67	0.10	-0.94	-1.54	-1.91	-2.30
BI HS BILS Oil House	0.00	0.00	0.00	0.78	-2.01	-3.01	-3.70	-4.14	-4.65
BI HS BILS Cistern North A	0.00	0.00	0.00	0.85	-2.01	-3.01	-3.70	-4.14	-4.64
BI HS BILS Cistern North B	0.00	0.00	0.00	0.89	-2.01	-3.01	-3.70	-4.14	-4.64
BI HS BILS Cistern South	0.00	0.00	0.00	0.93	-2.01	-3.01	-3.70	-4.14	-4.64
BI HS BILS LH	1.58	0.64	0.85	0.78	-0.43	-1.43	-2.12	-2.56	-3.07
BI HS LH Store House	1.77	0.92	1.04	0.87	-0.24	-1.24	-1.92	-2.36	-2.86
BI HS KQ & Visitors Center	2.00	0.81	1.26	0.94	-0.01	-1.01	-1.70	-2.14	-2.65
HI HS LK Main House	4.65	1.36	1.59	1.48	2.60	1.55	0.65	0.19	-0.11
HI HS LK Boathouse	1.92	0.88	1.19	1.50	-0.13	-1.18	-2.08	-2.54	-2.84
HI HS LK Kitchen	1.83	0.85	1.10	1.25	-0.22	-1.28	-2.18	-2.64	-2.94
HI HS CCC Cabin 321	7.52	6.54	6.79	6.70	7.12	7.12	7.12	7.12	7.12
HI HS CCC Cabin 322	9.00	8.01	8.27	8.16	8.60	8.60	8.60	8.60	8.60
HI HS CCC Cabin 323	9.32	8.08	8.59	8.26	8.92	8.92	8.92	8.92	8.92
HI HS CCC Cabin 324	0.00	0.00	0.00	7.99	-0.40	-0.40	-0.40	-0.40	-0.40
HI HS CAHA LH	5.05	2.85	3.15	3.09	4.65	4.65	1.52	1.19	0.83
HI HS CAHA LH Oilhouse	3.42	2.58	2.69	2.92	3.02	0.13	-0.11	-0.43	-0.79
HI HS CAHA Principal KQ	3.43	2.48	3.22	2.86	3.03	0.13	-0.10	-0.42	-0.78
HI HS CAHA Double KQ	3.68	2.49	3.16	3.15	3.28	0.37	0.14	-0.17	-0.53
HI HS CG & Ranger Station	3.64	2.43	2.51	2.67	3.24	0.30	0.10	-0.20	-0.54
HI HS CG Equipment Shed	3.76	2.28	3.48	2.43	3.36	0.42	0.22	-0.09	-0.42
HI HS HWB	2.61	0.60	0.82	0.90	0.70	-0.03	-0.55	-0.78	-0.92
HI HS HWB Shed 1	1.54	0.62	0.81	0.74	-0.37	-1.09	-1.61	-1.85	-1.99
HI HS HWB Flag House	1.34	0.48	0.60	0.80	-0.58	-1.30	-1.82	-2.06	-2.19
OI BD Oil House	0.00	0.00	0.00	1.13	-1.70	-2.22	-2.55	-2.94	-3.64
OI HS Ocracoke LH	1.76	0.94	1.02	1.39	1.36	-0.46	-0.79	-1.18	-1.88
OI HS Keepers Quarters	1.79	0.62	1.06	0.94	0.09	-0.43	-0.76	-1.16	-1.86
OI HS Tool House	1.86	0.90	1.13	1.03	0.17	-0.35	-0.68	-1.08	-1.78
OI HS Privy	0.00	0.00	0.00	1.14	-1.70	-2.22	-2.55	-2.94	-3.64

Table 8. Present-day-plus-70-cm-sea-level-rise vulnerability estimates of storm-surge flooding for CAHA sites and structures.

CAHA Sites & Structures	FFE (m)	LAG (m)	HAG (m)	DEM (m)	FFE - c1 (m)	FFE - c2 (m)	FEE -c3 (m)	FFE - c4 (m)	FFE - c5 (m)
BI HS CG Station (Hilton)	2.59	1.17	1.86	1.68	0.20	-0.84	-1.43	-1.80	-2.18
BI HS LS&RS	2.19	1.18	1.46	1.67	-0.20	-1.24	-1.84	-2.21	-2.60
BI HS BILS Oil House	0.00	0.00	0.00	0.78	-2.31	-3.31	-4.00	-4.44	-4.95
BI HS BILS Cistern North A	0.00	0.00	0.00	0.85	-2.31	-3.31	-4.00	-4.44	-4.94
BI HS BILS Cistern North B	0.00	0.00	0.00	0.89	-2.31	-3.31	-4.00	-4.44	-4.94
BI HS BILS Cistern South	0.00	0.00	0.00	0.93	-2.31	-3.31	-4.00	-4.44	-4.94
BI HS BILS LH	1.58	0.64	0.85	0.78	-0.73	-1.73	-2.42	-2.86	-3.37
BI HS LH Store House	1.77	0.92	1.04	0.87	-0.54	-1.54	-2.22	-2.66	-3.16
BI HS KQ & Visitors Center	2.00	0.81	1.26	0.94	-0.31	-1.31	-2.00	-2.44	-2.95
HI HS LK Main House	4.65	1.36	1.59	1.48	2.30	1.25	0.35	-0.11	-0.41
HI HS LK Boathouse	1.92	0.88	1.19	1.50	-0.43	-1.48	-2.38	-2.84	-3.14
HI HS LK Kitchen	1.83	0.85	1.10	1.25	-0.52	-1.58	-2.48	-2.94	-3.24
HI HS CCC Cabin 321	7.52	6.54	6.79	6.70	6.82	6.82	6.82	6.82	6.82
HI HS CCC Cabin 322	9.00	8.01	8.27	8.16	8.30	8.30	8.30	8.30	8.30
HI HS CCC Cabin 323	9.32	8.08	8.59	8.26	8.62	8.62	8.62	8.62	8.62
HI HS CCC Cabin 324	0.00	0.00	0.00	7.99	-0.70	-0.70	-0.70	-0.70	-0.70
HI HS CAHA LH	5.05	2.85	3.15	3.09	4.35	4.35	1.22	0.89	0.53
HI HS CAHA LH Oilhouse	3.42	2.58	2.69	2.92	2.72	-0.17	-0.41	-0.73	-1.09
HI HS CAHA Principal KQ	3.43	2.48	3.22	2.86	2.73	-0.17	-0.40	-0.72	-1.08
HI HS CAHA Double KQ	3.68	2.49	3.16	3.15	2.98	0.07	-0.16	-0.47	-0.83
HI HS CG & Ranger Station	3.64	2.43	2.51	2.67	2.94	0.00	-0.20	-0.50	-0.84
HI HS CG Equipment Shed	3.76	2.28	3.48	2.43	3.06	0.12	-0.08	-0.39	-0.72
HI HS HWB	2.61	0.60	0.82	0.90	0.40	-0.33	-0.85	-1.08	-1.22
HI HS HWB Shed 1	1.54	0.62	0.81	0.74	-0.67	-1.39	-1.91	-2.15	-2.29
HI HS HWB Flag House	1.34	0.48	0.60	0.80	-0.88	-1.60	-2.12	-2.36	-2.49
OI BD Oil House	0.00	0.00	0.00	1.13	-2.00	-2.52	-2.85	-3.24	-3.94
OI HS Ocracoke LH	1.76	0.94	1.02	1.39	1.06	-0.76	-1.09	-1.48	-2.18
OI HS Keepers Quarters	1.79	0.62	1.06	0.94	-0.21	-0.73	-1.06	-1.46	-2.16
OI HS Tool House	1.86	0.90	1.13	1.03	-0.13	-0.65	-0.98	-1.38	-2.08
OI HS Privy	0.00	0.00	0.00	1.14	-2.00	-2.52	-2.85	-3.24	-3.94

Table 9. Present-day-plus-100-cm-sea-level-rise vulnerability estimates of storm-surge flooding for CAHA sites and structures.

CAHA Sites & Structures	FFE (m)	LAG (m)	HAG (m)	DEM (m)	FFE - c1 (m)	FFE - c2 (m)	FEE -c3 (m)	FFE - c4 (m)	FFE - c5 (m)
BI HS CG Station (Hilton)	2.59	1.17	1.86	1.68	-0.10	-1.14	-1.73	-2.10	-2.48
BI HS LS&RS	2.19	1.18	1.46	1.67	-0.50	-1.54	-2.14	-2.51	-2.90
BI HS BILS Oil House	0.00	0.00	0.00	0.78	-2.61	-3.61	-4.30	-4.74	-5.25
BI HS BILS Cistern North A	0.00	0.00	0.00	0.85	-2.61	-3.61	-4.30	-4.74	-5.24
BI HS BILS Cistern North B	0.00	0.00	0.00	0.89	-2.61	-3.61	-4.30	-4.74	-5.24
BI HS BILS Cistern South	0.00	0.00	0.00	0.93	-2.61	-3.61	-4.30	-4.74	-5.24
BI HS BILS LH	1.58	0.64	0.85	0.78	-1.03	-2.03	-2.72	-3.16	-3.67
BI HS LH Store House	1.77	0.92	1.04	0.87	-0.84	-1.84	-2.52	-2.96	-3.46
BI HS KQ & Visitors Center	2.00	0.81	1.26	0.94	-0.61	-1.61	-2.30	-2.74	-3.25
HI HS LK Main House	4.65	1.36	1.59	1.48	2.00	0.95	0.05	-0.41	-0.71
HI HS LK Boathouse	1.92	0.88	1.19	1.50	-0.73	-1.78	-2.68	-3.14	-3.44
HI HS LK Kitchen	1.83	0.85	1.10	1.25	-0.82	-1.88	-2.78	-3.24	-3.54
HI HS CCC Cabin 321	7.52	6.54	6.79	6.70	6.52	6.52	6.52	6.52	6.52
HI HS CCC Cabin 322	9.00	8.01	8.27	8.16	8.00	8.00	8.00	8.00	8.00
HI HS CCC Cabin 323	9.32	8.08	8.59	8.26	8.32	8.32	8.32	8.32	8.32
HI HS CCC Cabin 324	0.00	0.00	0.00	7.99	-1.00	-1.00	-1.00	-1.00	-1.00
HI HS CAHA LH	5.05	2.85	3.15	3.09	4.05	4.05	0.92	0.59	0.23
HI HS CAHA LH Oilhouse	3.42	2.58	2.69	2.92	2.42	-0.47	-0.71	-1.03	-1.39
HI HS CAHA Principal KQ	3.43	2.48	3.22	2.86	2.43	-0.47	-0.70	-1.02	-1.38
HI HS CAHA Double KQ	3.68	2.49	3.16	3.15	2.68	-0.23	-0.46	-0.77	-1.13
HI HS CG & Ranger Station	3.64	2.43	2.51	2.67	2.64	-0.30	-0.50	-0.80	-1.14
HI HS CG Equipment Shed	3.76	2.28	3.48	2.43	2.76	-0.18	-0.38	-0.69	-1.02
HI HS HWB	2.61	0.60	0.82	0.90	0.10	-0.63	-1.15	-1.38	-1.52
HI HS HWB Shed 1	1.54	0.62	0.81	0.74	-0.97	-1.69	-2.21	-2.45	-2.59
HI HS HWB Flag House	1.34	0.48	0.60	0.80	-1.18	-1.90	-2.42	-2.66	-2.79
OI BD Oil House	0.00	0.00	0.00	1.13	-2.30	-2.82	-3.15	-3.54	-4.24
OI HS Ocracoke LH	1.76	0.94	1.02	1.39	0.76	-1.06	-1.39	-1.78	-2.48
OI HS Keepers Quarters	1.79	0.62	1.06	0.94	-0.51	-1.03	-1.36	-1.76	-2.46
OI HS Tool House	1.86	0.90	1.13	1.03	-0.43	-0.95	-1.28	-1.68	-2.38
OI HS Privy	0.00	0.00	0.00	1.14	-2.30	-2.82	-3.15	-3.54	-4.24

Table 10. Present-day-plus-140-cm-sea-level-rise vulnerability estimates of storm-surge flooding for CAHA sites and structures.

CAHA Sites & Structures	FFE (m)	LAG (m)	HAG (m)	DEM (m)	FFE - c1 (m)	FFE - c2 (m)	FEE -c3 (m)	FFE - c4 (m)	FFE - c5 (m)
BI HS CG Station (Hilton)	2.59	1.17	1.86	1.68	-0.50	-1.54	-2.13	-2.50	-2.88
BI HS LS&RS	2.19	1.18	1.46	1.67	-0.90	-1.94	-2.54	-2.91	-3.30
BI HS BILS Oil House	0.00	0.00	0.00	0.78	-3.01	-4.01	-4.70	-5.14	-5.65
BI HS BILS Cistern North A	0.00	0.00	0.00	0.85	-3.01	-4.01	-4.70	-5.14	-5.64
BI HS BILS Cistern North B	0.00	0.00	0.00	0.89	-3.01	-4.01	-4.70	-5.14	-5.64
BI HS BILS Cistern South	0.00	0.00	0.00	0.93	-3.01	-4.01	-4.70	-5.14	-5.64
BI HS BILS LH	1.58	0.64	0.85	0.78	-1.43	-2.43	-3.12	-3.56	-4.07
BI HS LH Store House	1.77	0.92	1.04	0.87	-1.24	-2.24	-2.92	-3.36	-3.86
BI HS KQ & Visitors Center	2.00	0.81	1.26	0.94	-1.01	-2.01	-2.70	-3.14	-3.65
HI HS LK Main House	4.65	1.36	1.59	1.48	1.60	0.55	-0.35	-0.81	-1.11
HI HS LK Boathouse	1.92	0.88	1.19	1.50	-1.13	-2.18	-3.08	-3.54	-3.84
HI HS LK Kitchen	1.83	0.85	1.10	1.25	-1.22	-2.28	-3.18	-3.64	-3.94
HI HS CCC Cabin 321	7.52	6.54	6.79	6.70	6.12	6.12	6.12	6.12	6.12
HI HS CCC Cabin 322	9.00	8.01	8.27	8.16	7.60	7.60	7.60	7.60	7.60
HI HS CCC Cabin 323	9.32	8.08	8.59	8.26	7.92	7.92	7.92	7.92	7.92
HI HS CCC Cabin 324	0.00	0.00	0.00	7.99	-1.40	-1.40	-1.40	-1.40	-1.40
HI HS CAHA LH	5.05	2.85	3.15	3.09	3.65	3.65	0.52	0.19	-0.17
HI HS CAHA LH Oilhouse	3.42	2.58	2.69	2.92	2.02	-0.87	-1.11	-1.43	-1.79
HI HS CAHA Principal KQ	3.43	2.48	3.22	2.86	2.03	-0.87	-1.10	-1.42	-1.78
HI HS CAHA Double KQ	3.68	2.49	3.16	3.15	2.28	-0.63	-0.86	-1.17	-1.53
HI HS CG & Ranger Station	3.64	2.43	2.51	2.67	2.24	-0.70	-0.90	-1.20	-1.54
HI HS CG Equipment Shed	3.76	2.28	3.48	2.43	2.36	-0.58	-0.78	-1.09	-1.42
HI HS HWB	2.61	0.60	0.82	0.90	-0.30	-1.03	-1.55	-1.78	-1.92
HI HS HWB Shed 1	1.54	0.62	0.81	0.74	-1.37	-2.09	-2.61	-2.85	-2.99
HI HS HWB Flag House	1.34	0.48	0.60	0.80	-1.58	-2.30	-2.82	-3.06	-3.19
OI BD Oil House	0.00	0.00	0.00	1.13	-2.70	-3.22	-3.55	-3.94	-4.64
OI HS Ocracoke LH	1.76	0.94	1.02	1.39	0.36	-1.46	-1.79	-2.18	-2.88
OI HS Keepers Quarters	1.79	0.62	1.06	0.94	-0.91	-1.43	-1.76	-2.16	-2.86
OI HS Tool House	1.86	0.90	1.13	1.03	-0.83	-1.35	-1.68	-2.08	-2.78
OI HS Privy	0.00	0.00	0.00	1.14	-2.70	-3.22	-3.55	-3.94	-4.64

Results from the preceding tables highlights individual structural vulnerability to each category of SLOSH storm MOM simulation as well as each category with a static rise of sea level. Although the vulnerability categories are arbitrarily chosen, they are consistent across SLR simulations and between districts and structures. This approach allows the comparison of risk between buildings (albeit without individual structural engineering, wave energy impacts). Thus, the results highlighted below from the preceding data are intended as a guide to potential site investigation of mitigation or adaptation options.

At the current baseline condition without additional relative SLR, the basic vulnerability highlights structures vulnerable to storm surge inundation:

- At present-day (Table 5), various ancillary and infrastructure are the most vulnerable to inundation at even category 1 storm surge at Bodie Island and Ocracoke (e.g, cisterns and oil house structures).
- In addition, today category 2 storm surges for direct landfalling hurricanes present a slight to moderate risk of inundation to a variety of significant structures, including the visitor center and life saving stations at Bodie Island and Little Kinnakeet.
- Slight to moderate risk are also posed by category 2 storms today on Ocracoke, including the lighthouse, keepers quarters and shed.

In tables 6-10, rising SLR presents a progression of increasing risk to structures with lower category of storm surges as SLR increases. Relative SLR of 20cm in Table 6 would be potentially realized between 2035-2055, depending on ensuing SLR. A mid-range estimate of relative SLR to reach 20cm in the CAHA region would be 2040-2045 (c.f., SLR curves of the NC CRC Science Panel (2010)).

- At 20cm of SLR (Table 6), the risk to several structures increases from minimal to slight for a category 1 storm, including the Bodie Island lighthouse and storehouse, Little Kinnakeet kitchen, shed and flag house at Hatteras Island. Present risks, already severe, also increase for cistems and oil house at Bodie Island.
- With a category 2 landfall (also Table 6), storm surge would present additional moderate risks to the Bodie Island Life Saving site structure, the visitors center, and Little Kinnakeet Boat House. These structures FFEs would be nearly 1m below the static surge height, which does not include wave action in the MOM modeling.

Tables 7-10 present SLR scenarios with surges that are further out with time and/or portray a SLR acceleration. Table 8, +40cm SLR, would be potentially realized as soon as the early 2050s (translating to a 1.4m SLR rise by 2100) or as late as 2100 (using a linear projection of the last ~100yrs.)

- Table 8 +40cm SLR foresees an expansion of risk for category 1 surges to affect a large array of structures, including the boat house at Little Kinnakeet and shed at Hatteras Weather Bureau.
- Maximal Category 2 surges at +40cm SLR will also potentially elevate risks for the Ocracoke Light, keepers quarters and tool house and the Bodie Island LS&RS and Hilton CG.
- Category 3 surges with +40cm SLR also increase in risk severity to moderate level for Ocracoke, with surges from the MOMs predicting heights 0.68 to 0.79 meters above the FFE of these structures.

Additional evaluation of Tables 8-10 is limited to discussion of the trends. These tables inherit a greater degree of uncertainty reflecting variation of eustatic SLR projections and climate models. The ranges of relative SLR in these tables cover +70cm to +140cm. These scenarios could be realized as soon as 2070 on the most aggressive SLR curve of the NC CRC Science Panel (1.4m rise by 2100). Generally, these scenarios and the timeframe are beyond the scope of work. Nonetheless, the progressive evolution of increasing risk and the potential severity illustrated in the tables is noteworthy.

In addition to the site- and structure-specific tables of surge, SLR, and susceptibility of the FFEs, we include a few summary graphs that depict the evolving risk across categories of hurricane surges, percentage of structures flooded by storm surge and sea level rise height.

- Figure 19 illustrates that present day sea level poses only a slight relative risk to most CAHA structures. The FFEs of the structures are higher than the SLOSH MOM surges for most category 1 storms (of course, non-inclusive of superimposed wave action.)
- Nonetheless, with category 3 storms at current sea level, a majority of the CAHA structures are categorized as slight risk or higher (almost 50% moderate to severe) of surge heights exceeding the FFEs (Figure 19). This figure provides a baseline for overall interpretation of the surges with SLR in Figures 20 and 21.

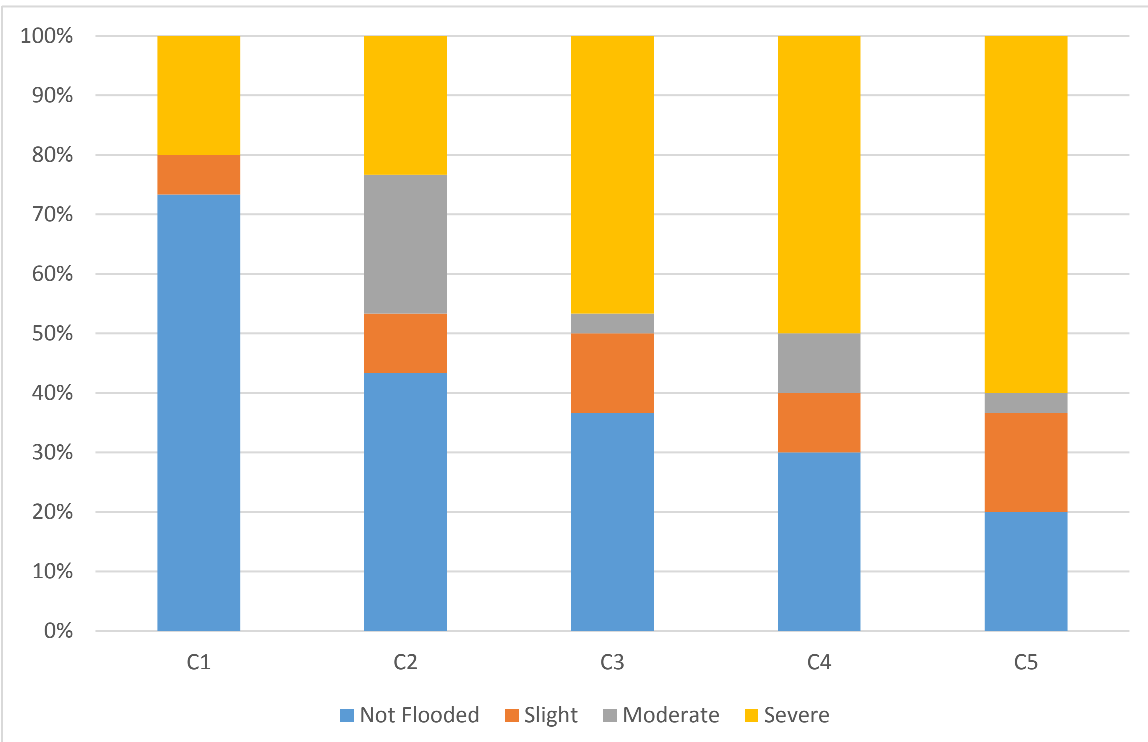


Fig. 19. Bar graph of percentage of NPS CAHA features flooded group storm surge category without projection of future flood risk from sea level rise. Data show that flooding is heavily dependent upon hurricane category.

To effect risk reduction for individual and overall CAHA historic resource assets, various adaptation or mitigation options would need to be explored and implemented. The results here illustrate that there is a growing threat with sea level rise, even if current climatology of tropical storms were to remain unchanged in magnitude.

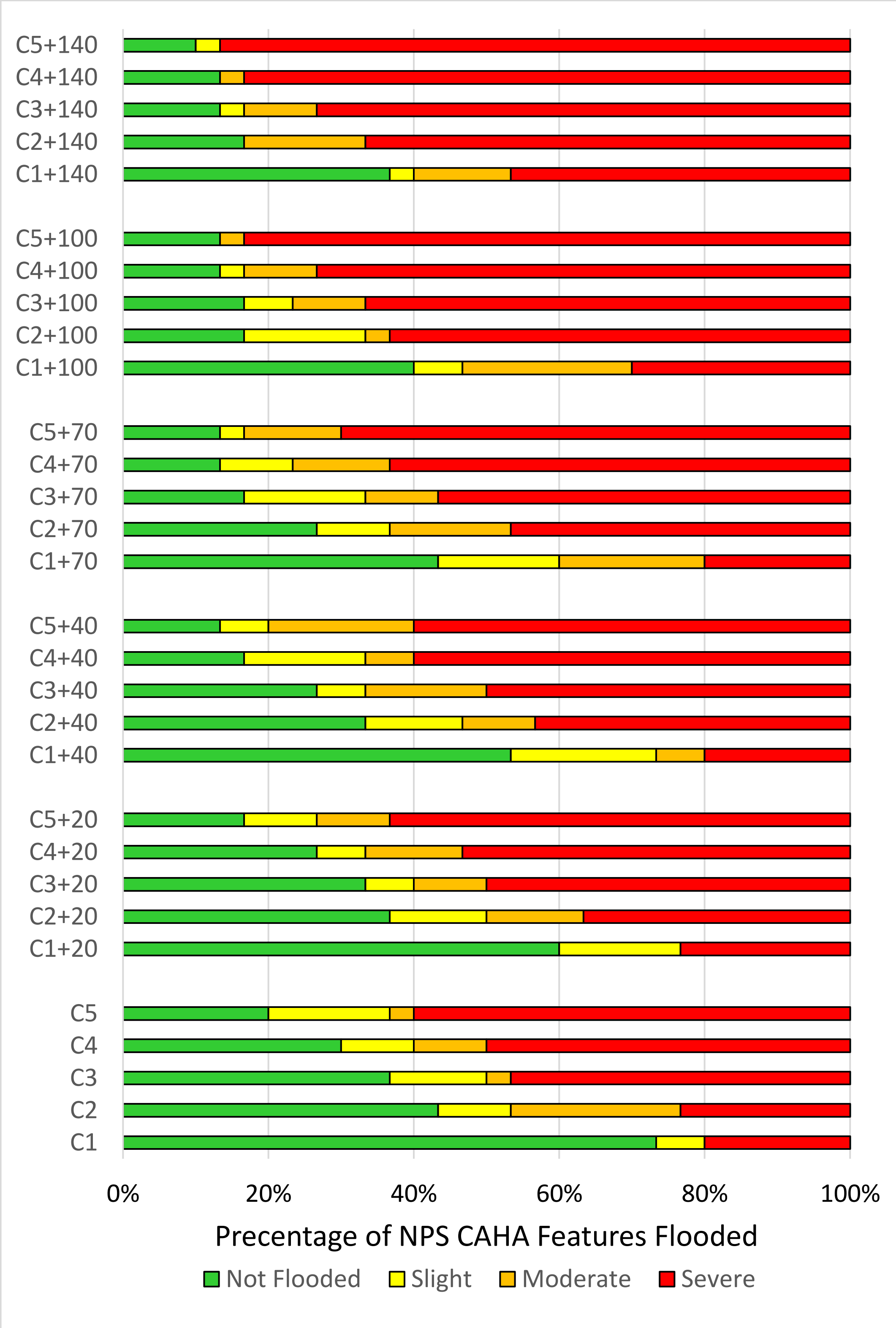


Fig. 20. Bar graph of percentage of NPS CAHA features flooded group by sea-level position. Data highlight how for any sea-level position, the amount of flood risk is heavily dependent upon hurricane category.

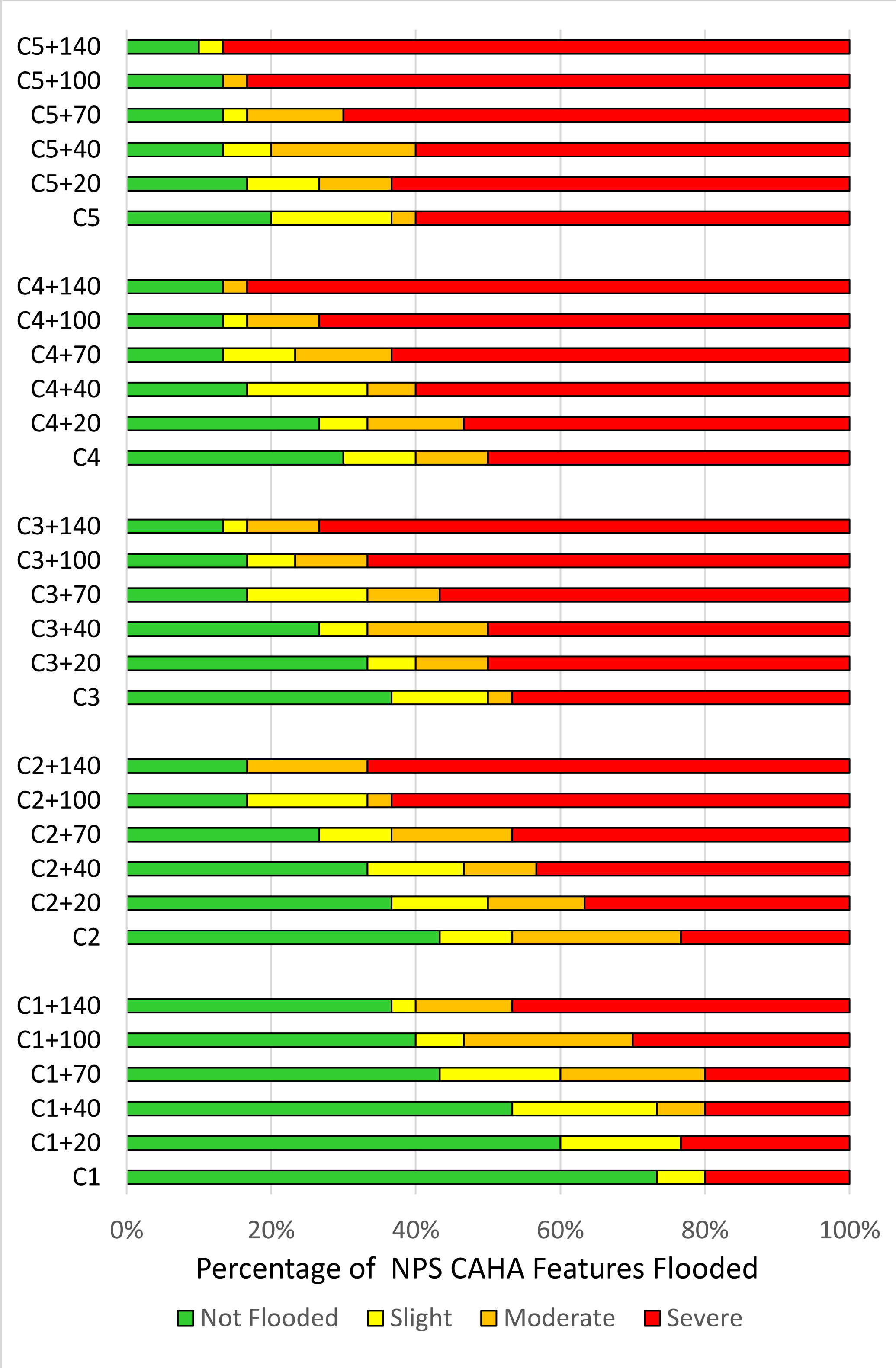


Fig. 21. Bar graph of percentage of NPS CAHA features flooded group by hurricane category. Data highlight how sea-level position (i.e., the amount of sea-level rise) has a significant control on the flooding impacts.

5. MITIGATION AND ADAPTATION

5.1 Coastal Erosion

The NC Coastal Erosion Study (2016) published by NC DCM provides a thorough review of the efforts that have been conducted by federal, state, and local governments, as well as academia, to study and address ocean coastal erosion. The Coastal Erosion Study (2016) also discusses mitigation activities that are currently being used throughout the State and potential strategies that should be considered in the future. Beach nourishment is the strategy that has been most commonly used along the NC coast to mitigate erosion for the purpose of protecting NC Route 12 and maintain the operation of the transportation system. Beach nourishment is an effective "soft" engineering alternative that does not result in some of the impacts that result from the "hard" engineering solutions implemented to mitigate erosion through the construction of erosion control structures like, groins, jetties, breakwaters, and seawalls. Unlike more permanent erosion control structures which attempt to inhibit natural processes that result in coastal erosion, beach nourishment acts as a buffer and wards off the threat of coastal erosion temporarily requiring periodic maintenance to preserve the effectiveness of the mitigation strategy over the long-term.

Table 12. Beach nourishment projects that have occurred throughout the study area according to the beach nourishment database maintained by the Program for the Study of Developed Shorelines at Western Carolina University.

Location	Episodes	Total Volume (cu. m)
Pea Island	16	5,923,697
Rodanthe	2	2,538,323
Buxton	3	1,385,374
Hatteras	7	678,773
Ocracoke Island	5	394,558
Total	33	10,920,724

A total of 33 beach nourishment episodes have occurred throughout the study area including the recently completed Mirlo Beach Nourishment project (September 2014), conducted to protect a section of NC 12, locally known as "S-Curves" or "S-Turns", north of Rodanthe. Although some of the episodes were conducted to fill areas where breaching occurred and inlets opened following extreme storm events, the majority of these episodes have occurred in the same areas that are susceptible to lower magnitude storm events and exhibit highly erosional long-term shoreline trends. For example, a low pressure weather system that tracked offshore of the Outer Banks on February 7th, 2016, caused overwash and breaching at Mirlo Beach in Rodanthe, the oceanfront of Buxton, and along the northern portion of Ocracoke Island.

Although beach nourishment reduces the vulnerability of coastal development along the oceanfront, maintaining the integrity and viability of the transportation system via N.C. 12 is the primary purpose of the projects that have been completed in the past as well as future scoped and proposed projects. NCDOT is the primary agency responsible for determining the feasibility of such projects and they have identified three sections of NC 12 south of Rodanthe in Dare and Hyde Counties that experienced overwash events in recent years and justified conducting feasibility studies as a preliminary step of the National Environmental Policy Act process to identify potential project scope, range of estimated costs of completion, and project-specific concerns related to preserving the NC 12 transportation corridor. The sections include:

- Buxton Canadian Hole "Hot Spot"
    - NC 12 from Avon to Buxton feasibility study was completed in December 2015
- Hatteras Village "Hot Spot"
    - NC 12 Hatteras Village feasibility study was completed in February 2016
- Ocracoke Island "Hot Spot"
    - Feasibility study has not yet been initiated

As a result of the NC 12 from Avon to Buxton Feasibility Study (2015) and according to Dare County, the Buxton Beach Nourishment Project will be constructed in 2017 and plans to widen 4.6 kilometers of oceanfront by approximately 75 meters for an estimated $25 million, with the majority of the funding coming from the Beach Nourishment Fund. Additional funding for this project will come from the establishment of a service district and is discussed in more detail below:

> *"On June 6, 2016 the Dare County Commissioners voted to establish a service district for the Buxton Beach Nourishment Project that includes parcels of land at the north end of Buxton located between Highway 12 and Old Lighthouse Road, and the four parcels north of Highway 12. This Service District went into effect with the new budget year on July 1 and the tax rate included in the 2017 Budget is 25 cents per $100 of valuation. This means that a property owner in the service district with a home assessed at $300,000 pays $750 in taxes. The tax rate is established each year by the Board of Commissioners as part of the annual budgeting process."* (Dare County, 2016).

The majority of the historical nourishment episodes that have occurred throughout the study area as well as both the recent Mirlo Beach Nourishment project and future Buxton Beach Nourishment project use hydraulic dredging techniques to pump sand on the beach. Beach nourishment using hydraulic dredging is an effective technique to supply sand to large project areas, but it is a costly option (as indicated by the estimated cost of the Buxton Beach Nourishment Project) that requires multi-agency coordination that can take years to complete from the time the project is identified as feasible, scoped, financed, permitted, and constructed. Although Dare County has (1) exhibited effective methods for financing nourishment projects through the establishment of the Beach Nourishment Fund and service district for the Buxton Beach Nourishment Project, and (2) been able to move through the regulatory process in order to conduct the beach nourishment, the identification of suitable source material may become a limiting factor that could reduce the viability of beach nourishment as an effective method to mitigate erosion in the future.

The Coastal Erosion Study (2016) identifies four major potential sand sources that could be used for future nourishment projects, but they would all require the use of hydraulic dredging techniques. Beach nourishment that uses hydraulic dredging techniques have an expensive mobilization cost and therefore are only cost effect for large scale projects. The study also mentions that nourishment projects can utilize sand trucked to the beach from an upland source. However, the use of this technique is often limited to smaller site-specific projects, and the proximity of quarries with availability material to the study area serves as another limiting factor. Regardless of the technique used the sediment must have similar characteristics as the native beach where it is being placed (15A NCAC 7H .0312) although an exemption is provided for sediment from regularly maintained navigation channels.

An alternative method of beach nourishment that was not discussed in the Coastal Erosion Study (2016) uses a technique known as "back-passing". Sand back-passing essentially harvests sand from accretional areas and deposits sand in erosional areas using excavators, dump trucks, and bulldozers. The method efficiently manages limited sand resources by reversing the natural migration of sediment along shore and "balances" the sediment budget. Although, large scale beach nourishment projects are the most effective for protecting infrastructure from coastal erosion by widening the beach to increase the buffer distance to the shoreline, or constructing large scale dunes to provide storm protection; back-passing can be an effective method to prolong the need for repetitive large scale re-nourishment projects.

Potential impacts with back-passing include disturbing shorebird nesting habitat or threatened plant species, or unearthing or damaging buried historical shipwrecks and cultural items (Hafner, 2012). However, these impacts can be easily avoided with strategic site selection and planning to conduct the work outside of nesting seasons. Additional impacts and costs of back-passing are associated with "wear and tear" on the roadway infrastructure as dump trucks haul sand from the excavation site to the deposition site. However, since the study area has a continuous linear shoreline impacts to the roadway can be avoided depending on the project scope.

Successful back-passing projects have recently been completed in multiple coastal communities in New Jersey[1] and can be referenced as an example. One critical factor associated with the back-passing projects is the development of a sediment budget. The New Jersey Beach Profile Network is surveyed bi-annually by the Stockton University Coastal Research Center and the results of the survey are used to identify trends in shoreline position. Quarterly surveys are conducted in areas that have erosional concerns using more densely spaced transects providing enough information to perform volumetric calculations. The Carteret County Shore Protection Office conducts a similar beach monitoring program that could also be used as an additional reference and perhaps a more suitable model for Dare and Hyde County to follow. It is recommended that Dare and Hyde County coordinate with the National Park Service unit of Cape Hatteras National Seashore to implement a beach monitoring program to identify sediment transport trends and develop effective management strategies to mitigate coastal erosion.

5.2 Storm Surge Flooding

Coastal flooding is the hazard with the longest history of hazard mitigation planning throughout the study region, primarily through participation in the National Flood Insurance Program (NFIP), which is administered by the Federal Emergency Management Agency (FEMA). The NFIP provides several regulatory products that participating communities use to support hazard mitigation through effective

[1] The City of Avalon, NJ first completed a pilot back-passing project that back-passed 44,000 cu. m of material in the spring of 2006 and then back-passed 42,000 cu. m of material in the spring of 2016. The Cities of North Wildwood (deposition site) and Wildwood (excavation site) have completed two back-passing projects. The first project back-passed 73,000 cu. m of material in the spring of 2012 and the second project back-passed 23,000 cu. m of material in the spring of 2016. A back-passing project was also completed in the City of Cape May to supplement a hydraulic dredging beach nourishment project by back-passing 53,000 cu. m of material in the winter of 2011.

floodplain management. Examples of these regulatory products include, Flood Insurance Study (FIS) Reports and Flood Insurance Rate Maps (FIRMs).

FIRMs contain critical pieces of information that are needed to support floodplain management and hazard mitigation planning such as floodplain boundaries, flood zones, and base flood elevations (BFEs). These regulatory products are developed using state of the art methods to 1) collect topographic and bathymetric conditions; 2) extensively model flood conditions from storm events with different probabilities for areas that are subject to both riverine and/or coastal flooding; and 3) facilitate the dissemination of flood risk information to the public, stakeholders, and community officials by hosting the adopted DFIRMs (Digital FIRMs) on interactive web mapping portals, such as the NC Flood Risk Information System (FRIS) developed by the NC Department of Public Safety.

Even though the coastal flood risk mapping process has been continually improved through the collaboration with various partners in other federal agencies, academia, and the private sector to more accurately determine flood risk along dynamic coastal areas; the FIRMs are primarily used to determine mandatory flood insurance purchase requirements as well as the insurance rate for properties that are mapped within a flood zone. The level of effort to collect baseline topographic and bathymetric data, perform flood modeling, and complete the map update process is immense and takes years to become finalized and adopted, especially if there are appeals. Since the FIRMs are developed as part of the NFIP, flood risk projects are completed on a rotating basis for communities throughout the country. It can take up to a decade or more for FIRMs[2] to be updated, with priority given to more densely populated areas. Therefore the level of flood risk can become inaccurate as time passes beyond the effective date of a FIRM; especially if significant geomorphic changes have occurred, or significant rates of sea level rise/land subsidence exist in the area since the most recent coastal flood risk study was completed.

Several web based tools have been developed by multiple federal agencies including the US Geological Survey (USGS) and the National Oceanic Atmospheric Administration (NOAA) to evaluate risk to coastal hazards. These web based tool can supplement regulatory products such as FIRMs and improve hazard mitigation planning. The USGS has developed the Coastal Change Hazards Portal, which provides interactive web mapping capabilities and downloadable data layers to analyze coastal change science along our Nation's coast. NOAA's Office for Coastal Management has performed a sea level rise mapping project at the regional level and made the Sea Level Rise (SLR) Viewer publicly available on the web so that coastal managers and scientists can use it as a screening tool to identify areas that are most vulnerable to sea level rise and increased flooding frequency. While the Coastal Change Hazards Portal and SLR Viewer are very useful tools for planning at the regional scale, decisions are often made at the individual property scale.

The purpose of the storm surge vulnerability assessment was to demonstrate a methodology that could be initiated by a GIS analyst within a government agency, whether federal, state, county or other to re-evaluate the vulnerability of coastal developments as new or updated information is acquired. For example, an assessment could be performed that identifies properties that have a FFE that is below the Base Flood Elevation associated with the location of the property on the effective and/or preliminary FIRMs. The assessment could also be repeated when new elevation data is acquired from coastal mapping projects that are either collected as routine surveys or following storm events in order to determine how vulnerability to storm surge changes in the interim between the release of new FIRMs. Elevation survey data with higher accuracy may also become available and the assessment could be repeated to determine if the vulnerability of properties in the surrounding areas changes (Allen *et al.*, 2010). For example, the

[2] The FIRMs available during for Dare County during this study were dated September 20, 2006 and Hyde County dated May 15, 2003.

assessment could be repeated once the Buxton Beach Nourishment project is completed to determine the effect the project has on reducing the vulnerability of the surrounding infrastructure. An assessment could also be performed using depth grids that take sea level rise into consideration since the Storm Surge Vulnerability maps that included sea level rise scenarios only displayed the potential extent of inundation.

5.3 Engagement

In addition to periodic meetings and briefings between ECU faculty, students, and NPS CAHA staff, we incorporated engagement into this project to both inform the analysis as well as obtain feedback from the community and other agencies conducting similar research. At the state level, we provided presentations that included NC Floodplain Mapping Program, Albemarle-Pamlico National Estuary Partnership, and local government and geospatial and emergency management professionals. These included presentations at the NC ArcUser Group Conference and Eastern Symposium, presentations at NOAA Coastal GeoTools, APNEP Decision Support Working Group, NC Geographic Information Coordinating Council, and the NC Hurricane Workshop. Locally, Ms. Donna Creef, Planning Director for Dare County, was contacted after project student Michael Flynn was awarded a NC Sea Grant Coastal Policy Fellowship to set up a meeting to discuss the work and alignment with existing efforts by the Dare County Planning Department. An initial meeting was held February 5th, 2016, at the Dare County Administration Building, which followed a meeting that was conducted with NPS staff to discuss progress on the cooperative agreement evaluating the vulnerability of the landmarks located within the Cape Hatteras National Seashore. Drew Pearson, Director of Emergency Management, was included and briefed on work for this CAHA project. We discussed how similar products could be developed for the communities located along the Outer Banks. These discussions resulted in participation in the Hurricane Preparedness and Safety Open House in May 2016.

A planning team consisting of Drew Pearson, Donna Creef, Noah Gillam, Sara Small, Holly White, and Kevin Zorc, worked together to host not only the first, but possibly inaugural annual event. The initial event was held on Friday, May 20th, 2016 from 3:00 to 8:00 pm at the Nags Head Fire Station 16, and a supplemental Open House was offered on Saturday, May 21st at the Fessenden Center in Buxton to provide an opportunity for members in communities that lived in the southern Hatteras Island. The event at the Nags Head Fire Station 16 consisted of displays, activities, and guest speakers of numerous organizations that provided information that could be used by the public to improve hurricane preparedness. Mayor Edwards and Commissioner Woodard attended the event and provided opening remarks. I gave a presentation about conducting the Multi-Hazard Vulnerability Assessment before the feature presentation on storm surge was given by Jamie Rhome, Team Lead of the Storm Surge Unit of the National Hurricane Center, which was followed by a presentation on forecasts and warnings given by Richard Bandy, Meteorologist-in-Charge at the NWS Newport/Morehead City Office.

Over 250 people attended the event and learned about tropical storms and hurricanes, flooding, citizen safety, mitigation construction products, and explored topics relative to the life cycle of disaster – preparedness, response, recovery, and mitigation. The attendees additionally enjoyed a cook out that was provided by the Nags Head Fire Department, and youth activities helped to make the event a truly inclusive community gathering that exemplified the best of a public/private partnership. Education and outreach is a critical component of hazard mitigation, and it is hoped that the Hurricane Preparedness and Safety Open House becomes an annual event that other communities can use as model. The event and collaboration with Dare County Planning spurred further interest and adoption of the same vulnerability assessment methodology for Outer Banks communities beyond the NPS Historic Districts.

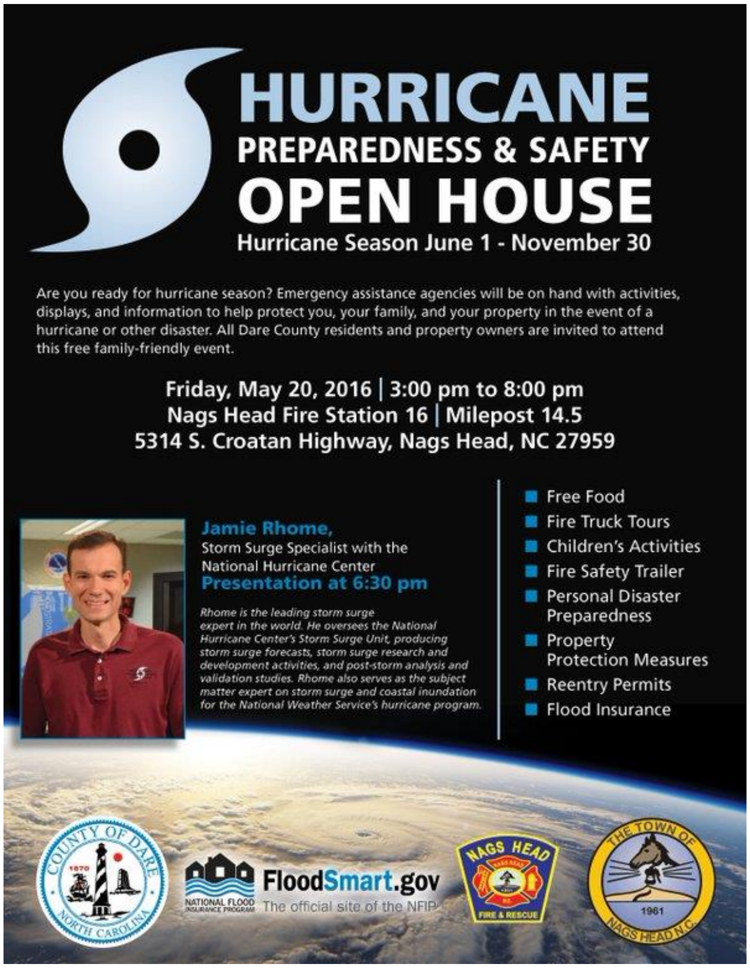


Figure 22. Promotional flyer advertising the Dare County open house event and a presentation on the NPS vulnerability assessment. A brief promotional video advertising the event was also prepared by Dare County and publicized via social media outlets.

5. CONCLUSION

The coastal development located along the Outer Banks and adjacent to the Cape Hatteras National Seashore is vulnerable to multiple coastal hazards including, coastal erosion, storm surge, and sea level rise. The purpose of this assessment was to determine the vulnerability of national historic landmarks to each hazard so that mitigation strategies can subsequently be developed. Results affirm the notion of increasing susceptibility to inundation and attendant coastal hazards with increasing sea level rise. This assessment also demonstrated a GIS-based methodology that can be repeated by GIS and vulnerability analysts in when updated information that was used in the assessment becomes available. The methodology is also adaptable and portable to other NPS parks and facilities and surrounding communities. Providing the public with access to this information may help to guide mitigation or adaptation strategies for individual and community property to collectively increase the resiliency of the region to multiple coastal hazards.

A number of limitations are notable for this study, necessarily constraining results and recommendations. First, the study made use primarily of existing data. The investigators required the best available coastal elevations and thus awaited the delivery of NC QL2 LiDAR, which pushed the study back several months. In addition, the availability of first floor elevation data was constrained; a mix of sources were initially found with variable documentation and unknown quality and accuracy. Hence, the project adopted a complete set of data from the NCFMP program (cross-checking against this in the field by spot-checking and against the limited FFEs from NPS.) Complex analytical steps required the conversion of all GIS data to a common vertical and horizontal datum, with some limitations and error inherently introduced in such processing. We were fortuitous with the release of a new SLOSH grid for the Hatteras region by the NWS National Hurricane Center, allowing some improvement to the downscaling of MOM inundation maps. Shoreline change analyses were completed for the oceanfront, but early in the project the team did not foresee the potential need to also include estuarine shoreline change and erosion rates. The vulnerability revealed by static SLR inundation for Bodie Island and, to a lesser degree, Little Kinnakeet, are suggestive of a need for closer examination of potential estuarine shoreline impacts to historic structures or ancillary facilities and roads at these sites. Similarly, island narrowing at other areas of CAHA, e.g., the Haulover or "Canadian Hole", may indicate a need to analyze estuarine shorelines for changes affecting park resources.

A number of insights and potential benefits of this project may also be synthesized for other NPS CAHA purposes. First, although this study focused on historic structures, there are also potential impacts of SLR to natural resources, habitats, and ecosystem services throughout CAHA. To some extent, the data acquired and modeling in this study could inform such analyses. Static SLR and SLOSH grids, LiDAR DEMs, and shoreline data, for instance, could be assimilated in models such as the Sea Level Affecting Marshes Model (SLAMM) to evaluate marsh fragmentation, loss, or migration up elevation. Shoreline change rates calculated in this study are an input parameter to SLAMM. The LiDAR DEMs for this project have been converted to a vertical datum that is relatively straightforward to transform for SLAMM wetland modeling (using tidal datums.) The approach taken to analyze structures across storm surge impacts and SLR levels is applicable to habitats and even recreational visitor activities (e.g., trails, kitesurfing, windsurfing, fishing, camping or ORV beach use.)

In the ensuing management application of this study, a few recommendations are also suggested to monitor and further predict sea level rise impacts on the park's cultural resources. The following specific tasks could improve management of these resources and any replication or follow-on study in the near-term:

- Monitor the periodic reporting of sea level trends by NOAA and the NC Division of Coastal Management.
    - The NOAA Office for Coastal Management continues to provide the Sea Level Rise Viewer application and to support other federal, state and local agencies with trend summaries, geospatial data, and analysis tools.
    - Other NOAA entities such as Tides and Currents provide real-time and historic information and trends. https://tidesandcurrents.noaa.gov/sltrends/sltrends.html
    - NC Division of Coastal Management coordinates the state's CRC Science Panel and tracking of trends for policy. Monitoring the DCM Sea Level site and its reports will facilitate reducing uncertainty for NC area projects of sea level rise

https://deq.nc.gov/about/divisions/coastal-management/coastal-management-hot-topics/sea-level-rise

- As SLR continues opportunities to improve risk assessments may evolve. NPS should evaluate newly available data from among various agencies.
    - New FEMA Digital Flood Insurance Rate Maps (FIRMs) in preliminary review for the Outer Banks counties will be released. FIRMs will continue to be a relevant coastal management policy device, directly and indirectly affecting land use. NPS efforts to relocate, elevate, or redesign its assets may be impacted by changes in FIRMs affecting the surrounding communities. In addition, modeling of FIRMS incorporates wave action and potential storm impacts. New FIRMs may reveal near-term changes in storm surge wave energy zones that were not available to this study.
    - The NC Floodplain Mapping Program has a strong record of procurement of high-resolution LiDAR elevation data, a critical component to this study. Future LiDAR, building and infrastructure data integrated by NCFMP may present a strong geospatial asset to the NPS.
    - The NC Coastal Atlas (https://www.nccoastalatlas.org/) and NC OneMap (http://data.nconemap.gov/geoportal/catalog/main/home.page) provide useful geospatial data repositories for the NPS CAHA and other NPS units in coastal North Carolina. The Atlas recently developed an inventory of coastal recreational assets, a coastal salinity database, and a series of "marsh migration potential" maps that could inform NPS planning for recreation or natural resources in CAHA.

6. ACKNOWLEDGMENTS

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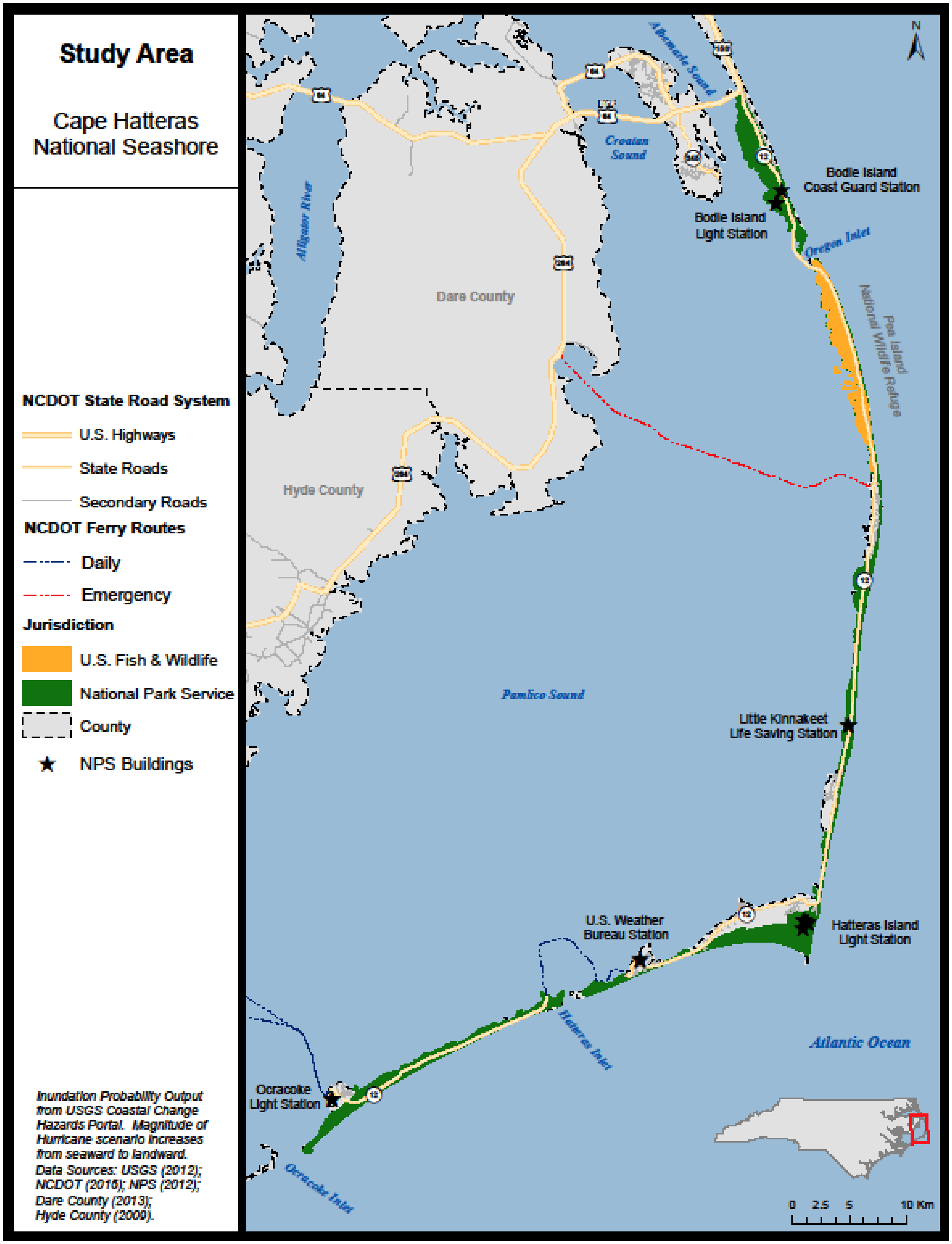
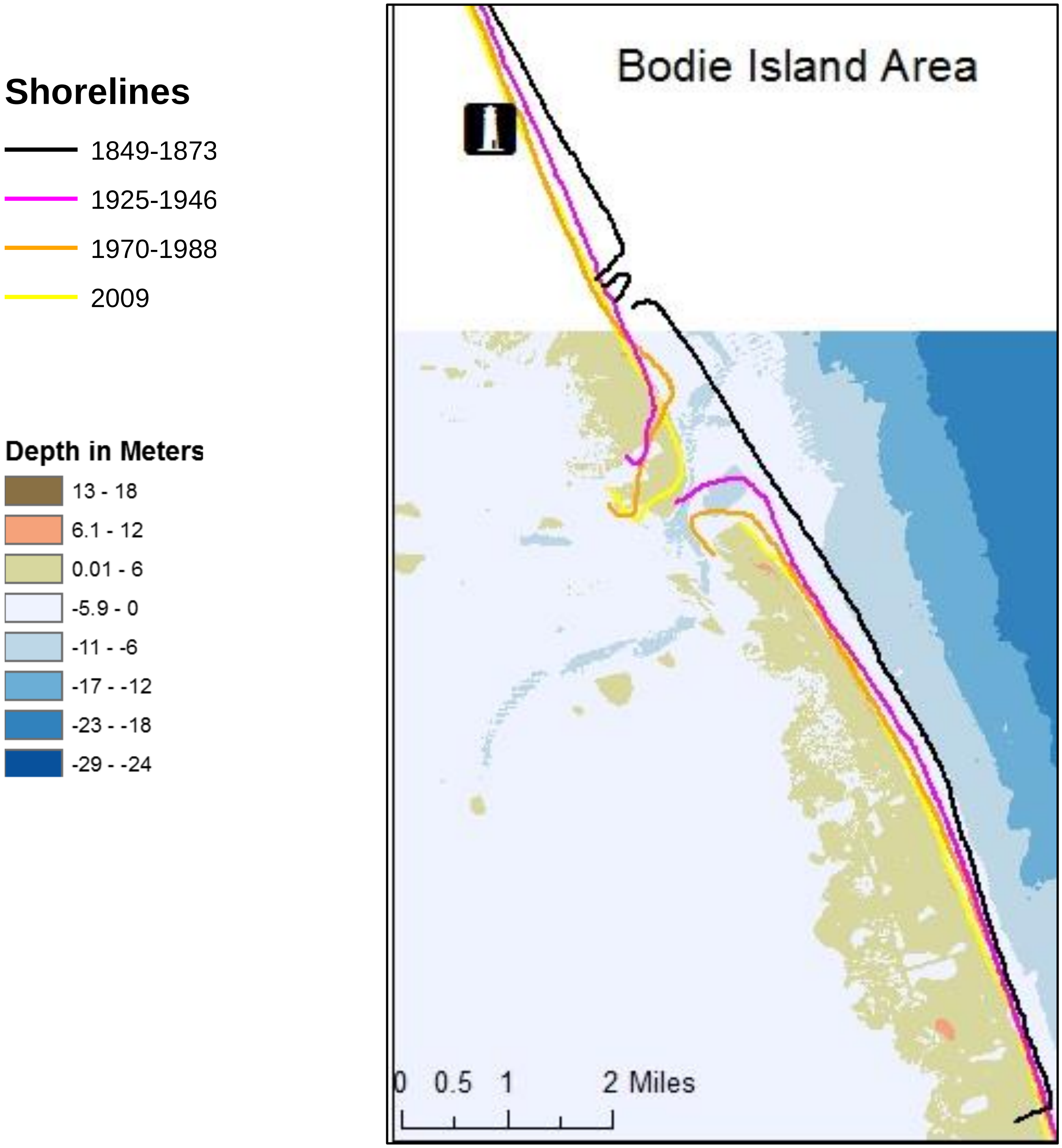
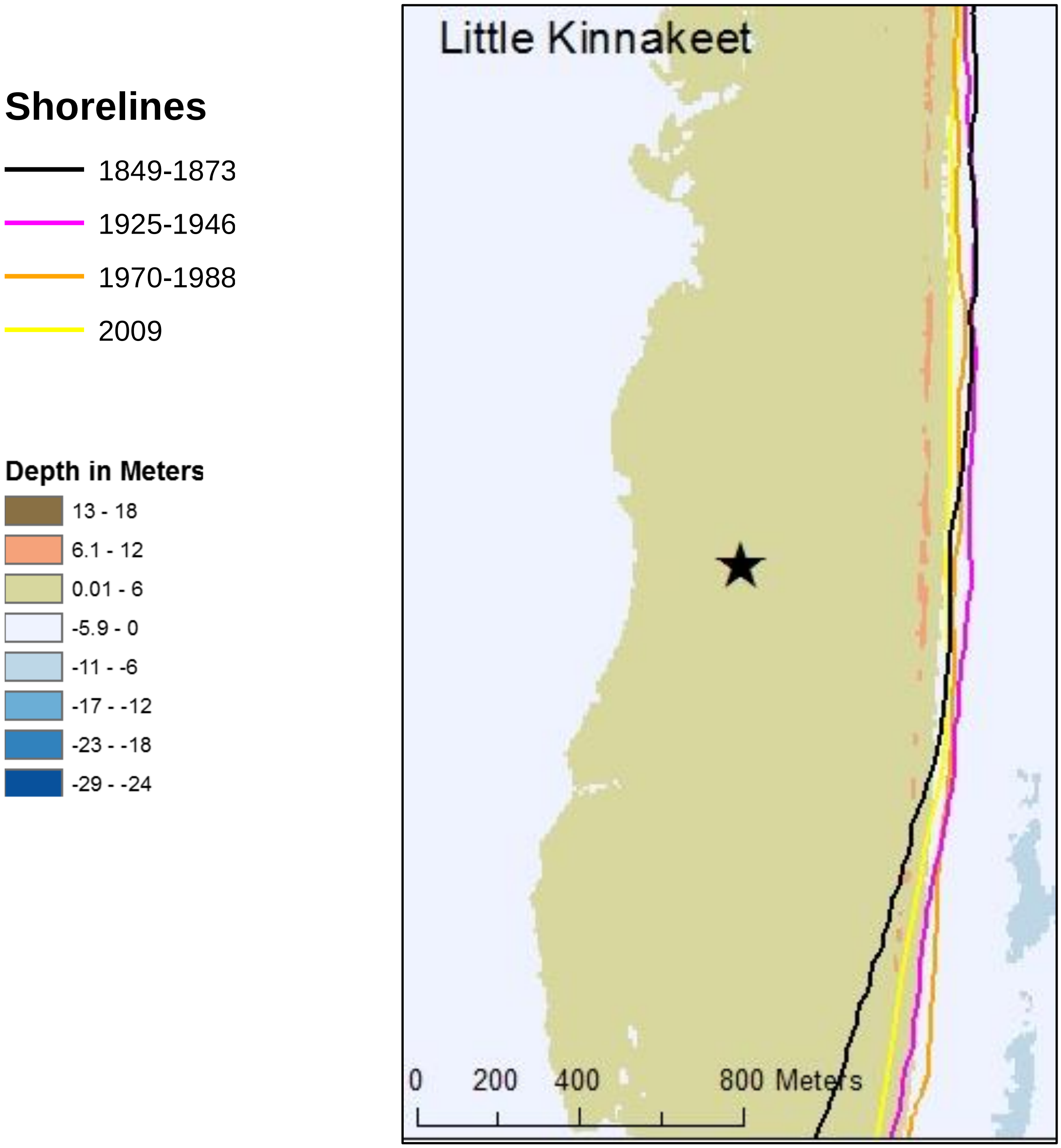
8. APPENDICES

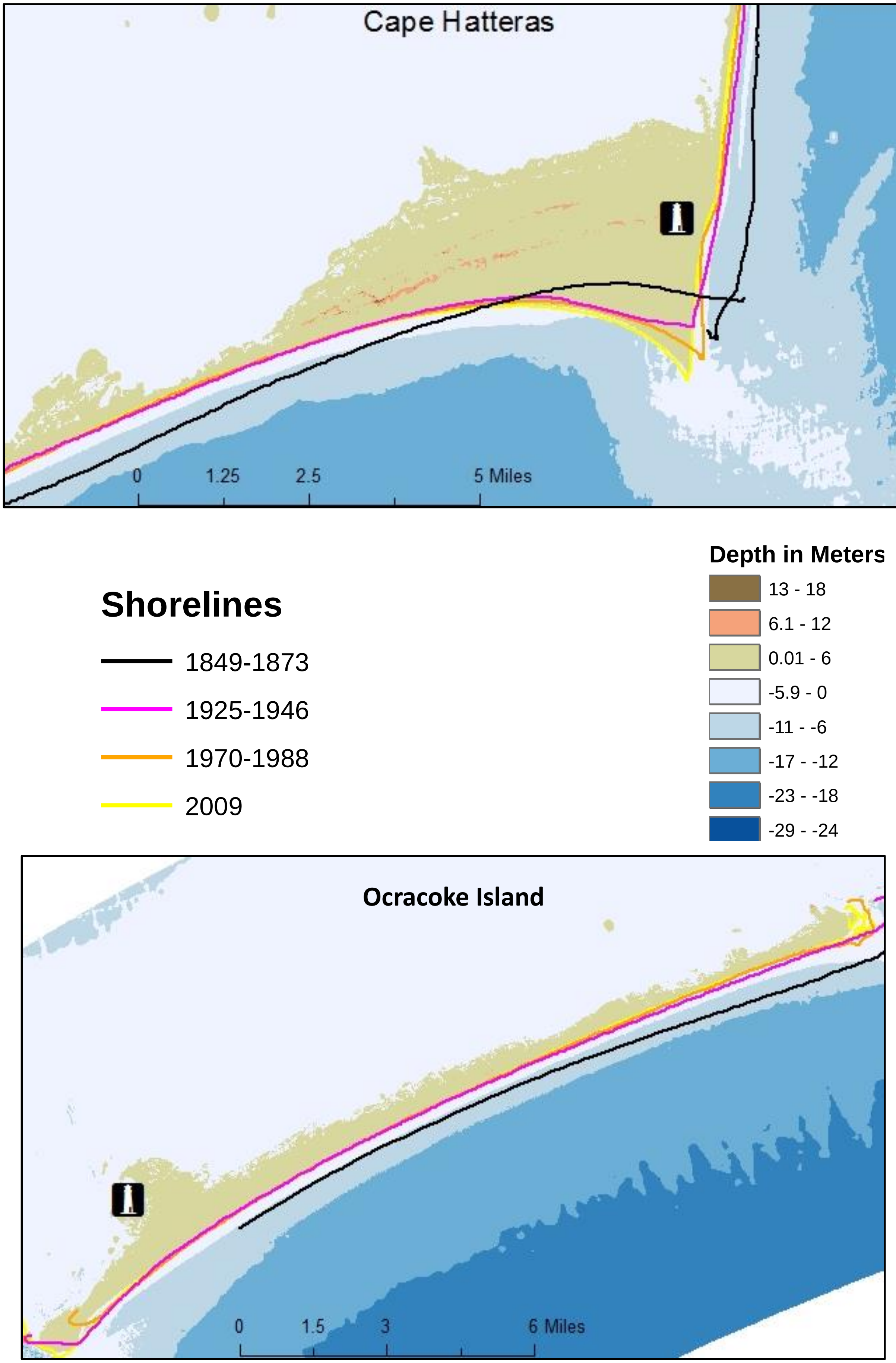
A. Study Area Location

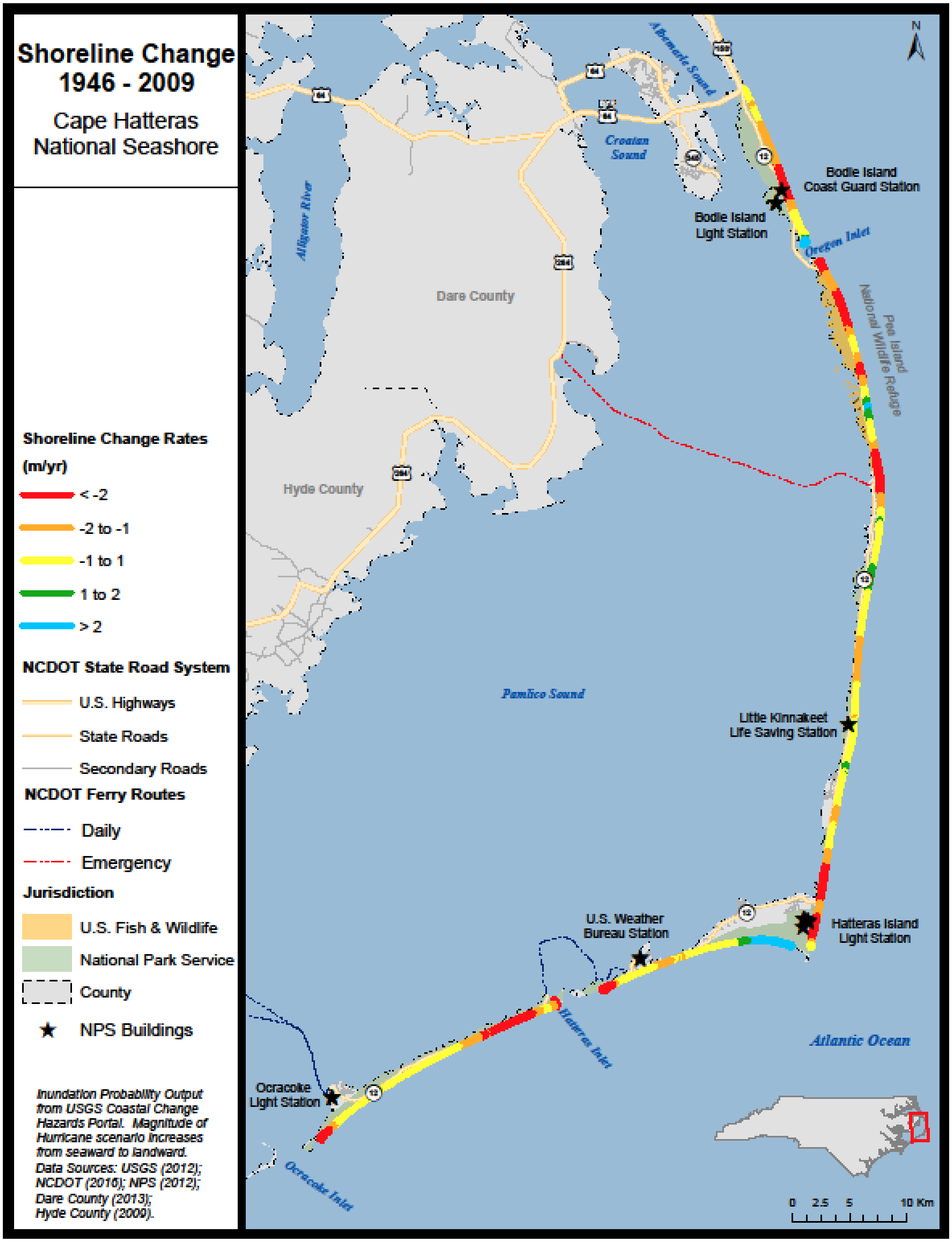


B. Historical Shoreline Changes in Districts

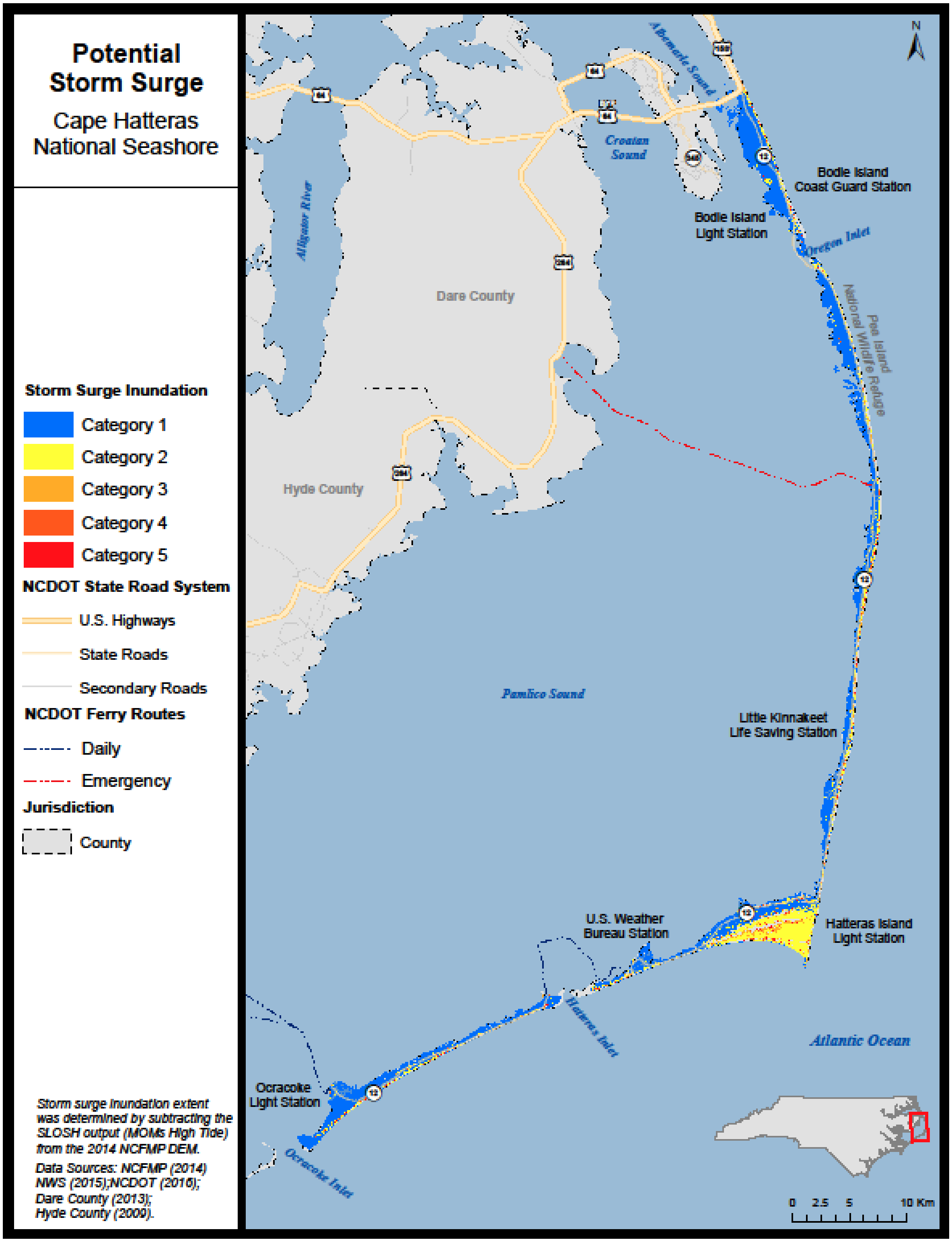


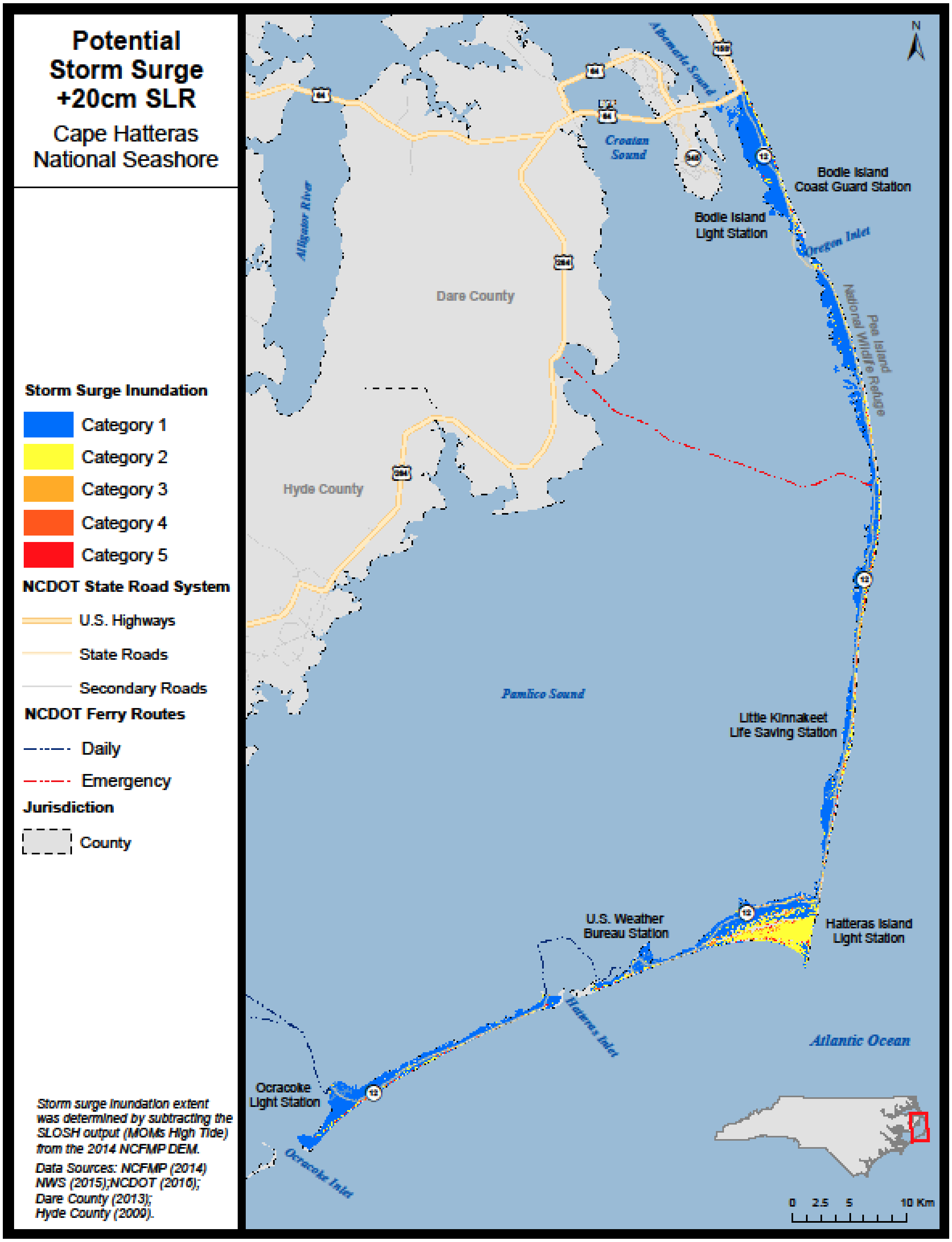

Shorelines
1849-1873
1925-1946
1970-1988
2009
Depth in Meters
13 - 18
6.1 - 12
0.01 - 6
-5.9 - 0
-11 - -6
-17 - -12
-23 - -18
-29 - -24
Little Kinnakeet
0 200 400 800 Meters

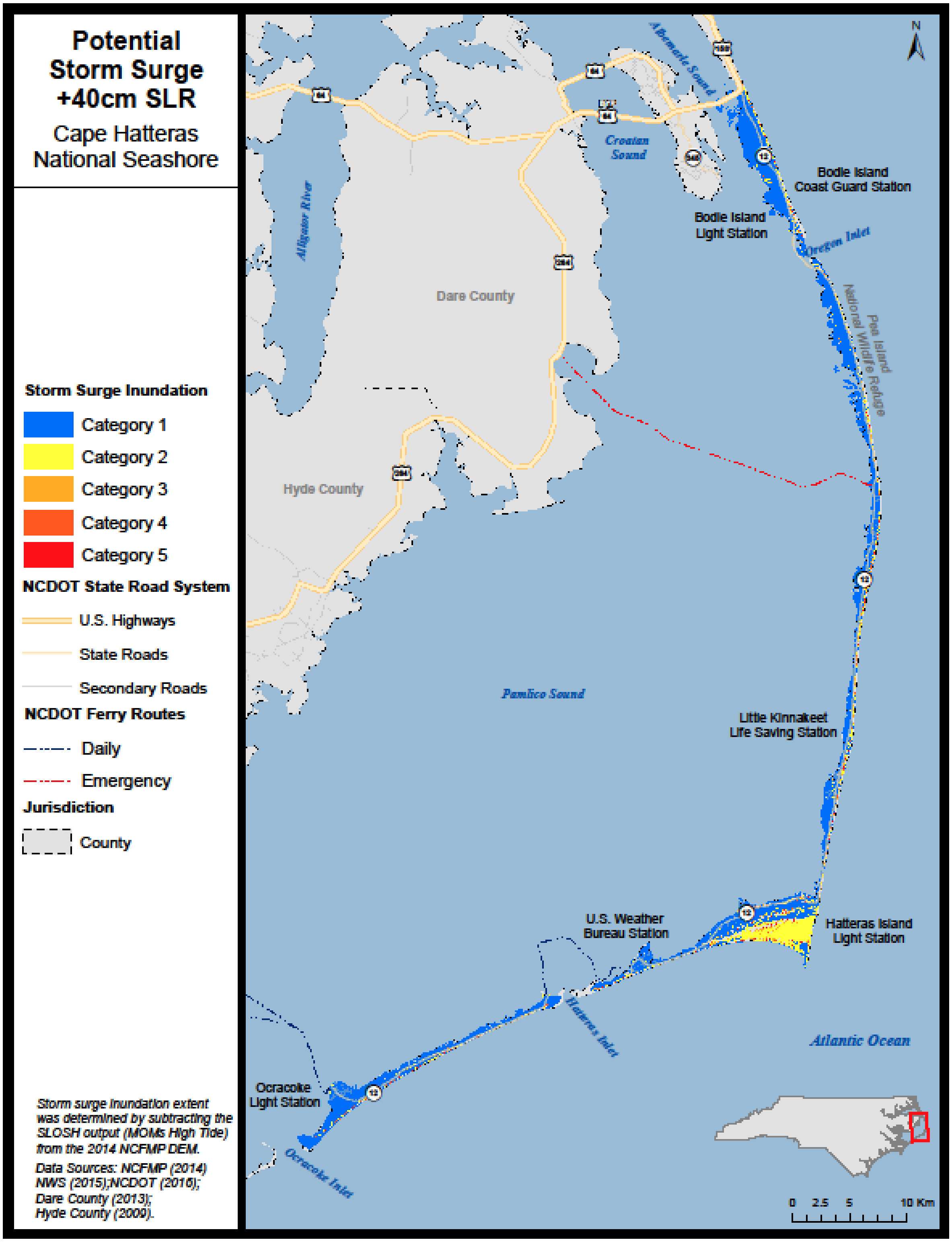

Cape Hatteras
0
1.25
2.5
5 Miles
Shorelines
1849-1873
1925-1946
1970-1988
2009
Depth in Meters
13 - 18
6.1 - 12
0.01 - 6
-5.9 - 0
-11 - -6
-17 - -12
-23 - -18
-29 - -24
Ocracoke Island
0
1.5
3
6 Miles

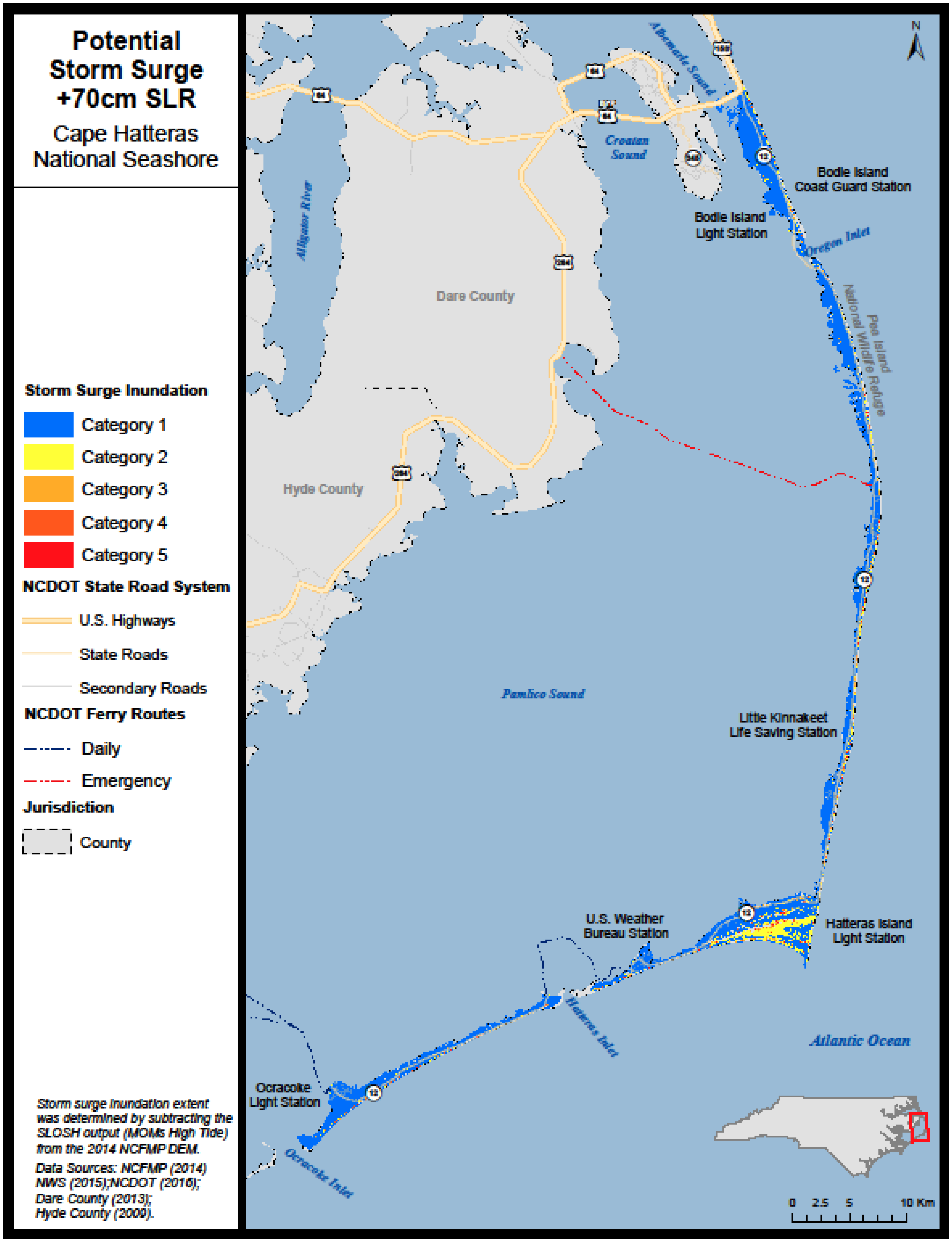

Shoreline Change 1946 - 2009
Cape Hatteras National Seashore
Shoreline Change Rates (m/yr)
< -2
-2 to -1
-1 to 1
1 to 2
> 2
NCDOT State Road System
U.S. Highways
State Roads
Secondary Roads
NCDOT Ferry Routes
Daily
Emergency
Jurisdiction
U.S. Fish & Wildlife
National Park Service
County
NPS Buildings
Inundation Probability Output from USGS Coastal Change Hazards Portal. Magnitude of Hurricane scenario increases from seaward to landward.
Data Sources: USGS (2012); NCDOT (2016); NPS (2012); Dare County (2013); Hyde County (2009).
Albemarle Sound
Croatan Sound
Alligator River
Dare County
Hyde County
Bodie Island Coast Guard Station
Bodie Island Light Station
Oregon Inlet
Pea Island National Wildlife Refuge
Pamlico Sound
Little Kinnakeet Life Saving Station
U.S. Weather Bureau Station
Hatteras Island Light Station
Hatteras Inlet
Atlantic Ocean
Ocracoke Light Station
Ocracoke Inlet
N
0 2.5 5 10 Km

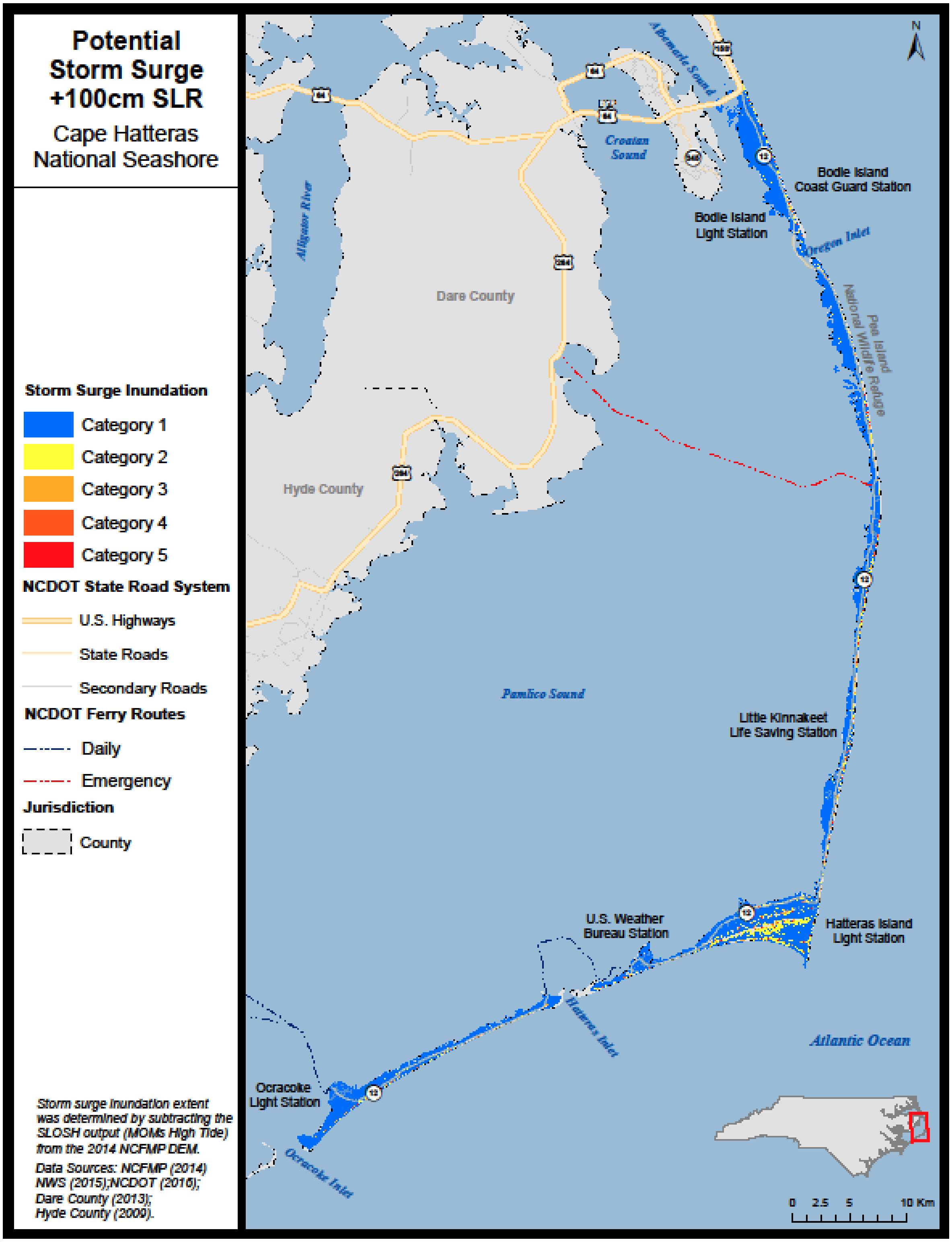
C. Potential Storm Surge Inundation by SLOSH MOM Category and Sea Level RiSe

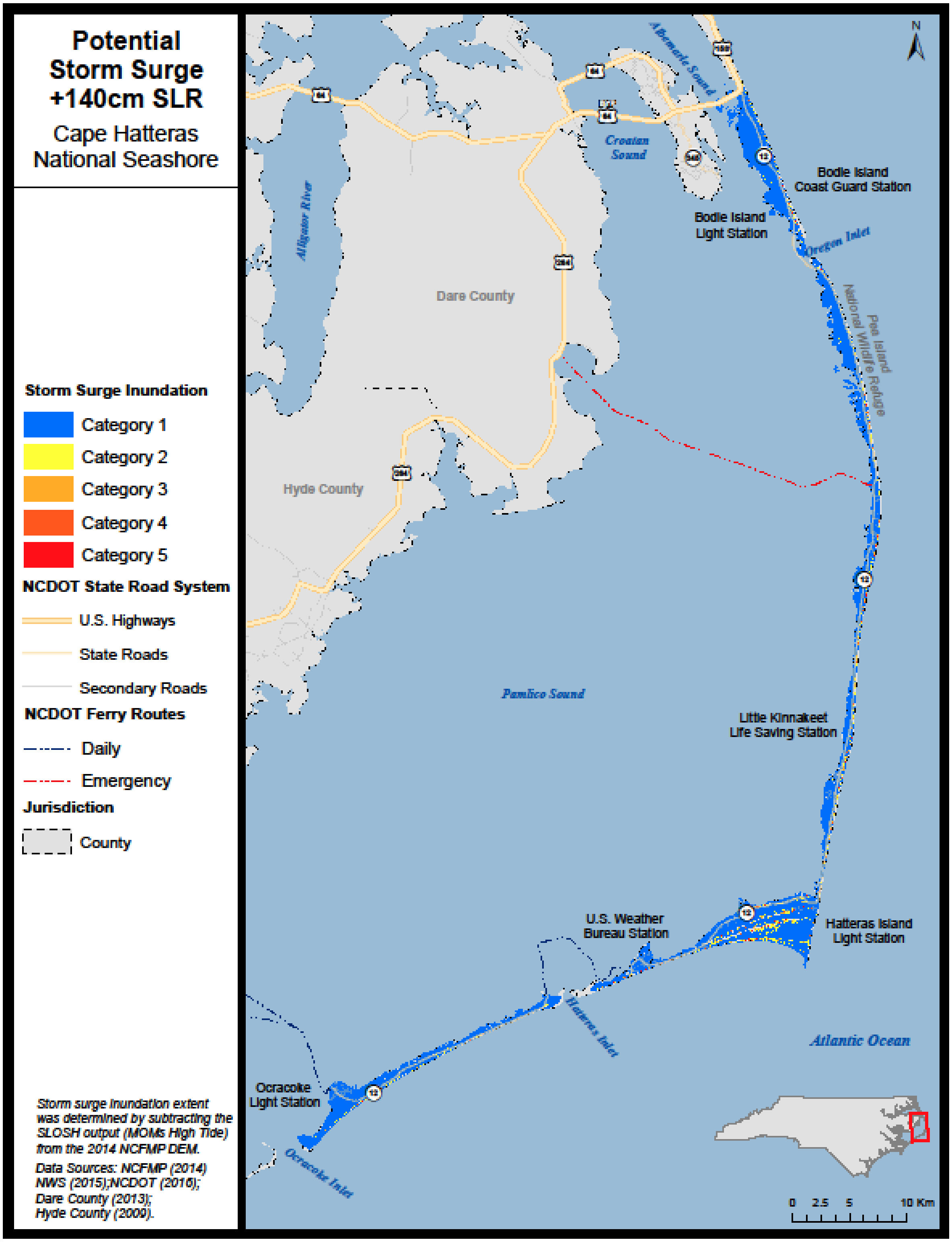



Potential
Storm Surge
+20cm SLR
Cape Hatteras
National Seashore
Storm Surge Inundation
Category 1
Category 2
Category 3
Category 4
Category 5
NCDOT State Road System
U.S. Highways
State Roads
Secondary Roads
NCDOT Ferry Routes
Daily
Emergency
Jurisdiction
County
Storm surge inundation extent was determined by subtracting the SLOSH output (MOMs High Tide) from the 2014 NCFMP DEM.
Data Sources: NCFMP (2014) NWS (2015);NCDOT (2016); Dare County (2013); Hyde County (2009).
Albemarle Sound
Croatan Sound
Alligator River
Dare County
Hyde County
Pamlico Sound
Bodie Island Coast Guard Station
Bodie Island Light Station
Oregon Inlet
Pea Island National Wildlife Refuge
Little Kinnakeet Life Saving Station
U.S. Weather Bureau Station
Hatteras Island Light Station
Hatteras Inlet
Atlantic Ocean
Ocracoke Light Station
Ocracoke Inlet
N
0 2.5 5 10 Km

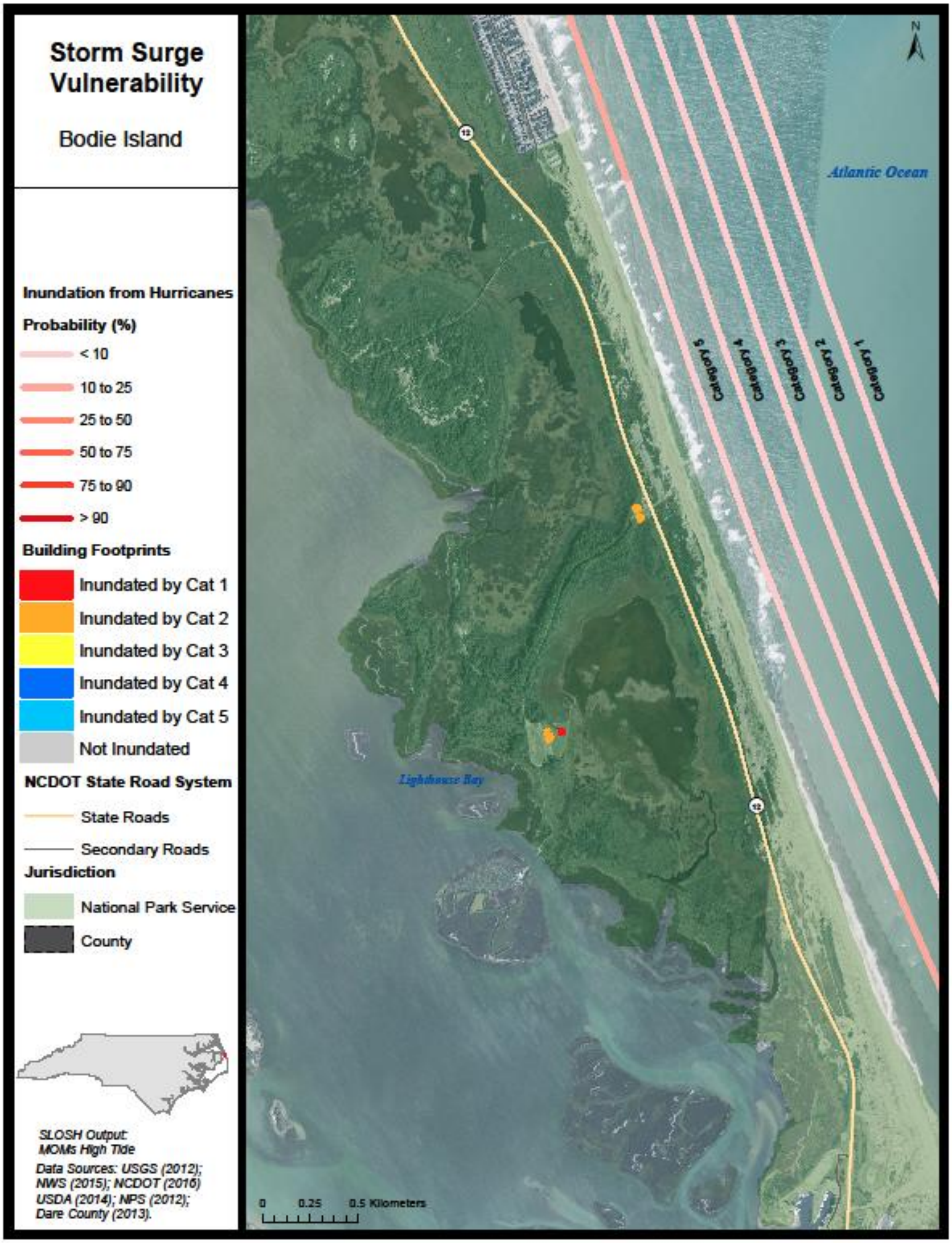

Potential Storm Surge +40cm SLR
Cape Hatteras National Seashore
Storm Surge Inundation
Category 1
Category 2
Category 3
Category 4
Category 5
NCDOT State Road System
U.S. Highways
State Roads
Secondary Roads
NCDOT Ferry Routes
Daily
Emergency
Jurisdiction
County
Storm surge inundation extent was determined by subtracting the SLOSH output (MOMs High Tide) from the 2014 NCFMP DEM.
Data Sources: NCFMP (2014) NWS (2015);NCDOT (2016); Dare County (2013); Hyde County (2009).
Albemarle Sound
Croatan Sound
Alligator River
Dare County
Hyde County
Pamlico Sound
Atlantic Ocean
Bodie Island Coast Guard Station
Bodie Island Light Station
Oregon Inlet
Pea Island National Wildlife Refuge
Little Kinnakeet Life Saving Station
U.S. Weather Bureau Station
Hatteras Island Light Station
Hatteras Inlet
Ocracoke Light Station
Ocracoke Inlet
N
0 2.5 5 10 Km

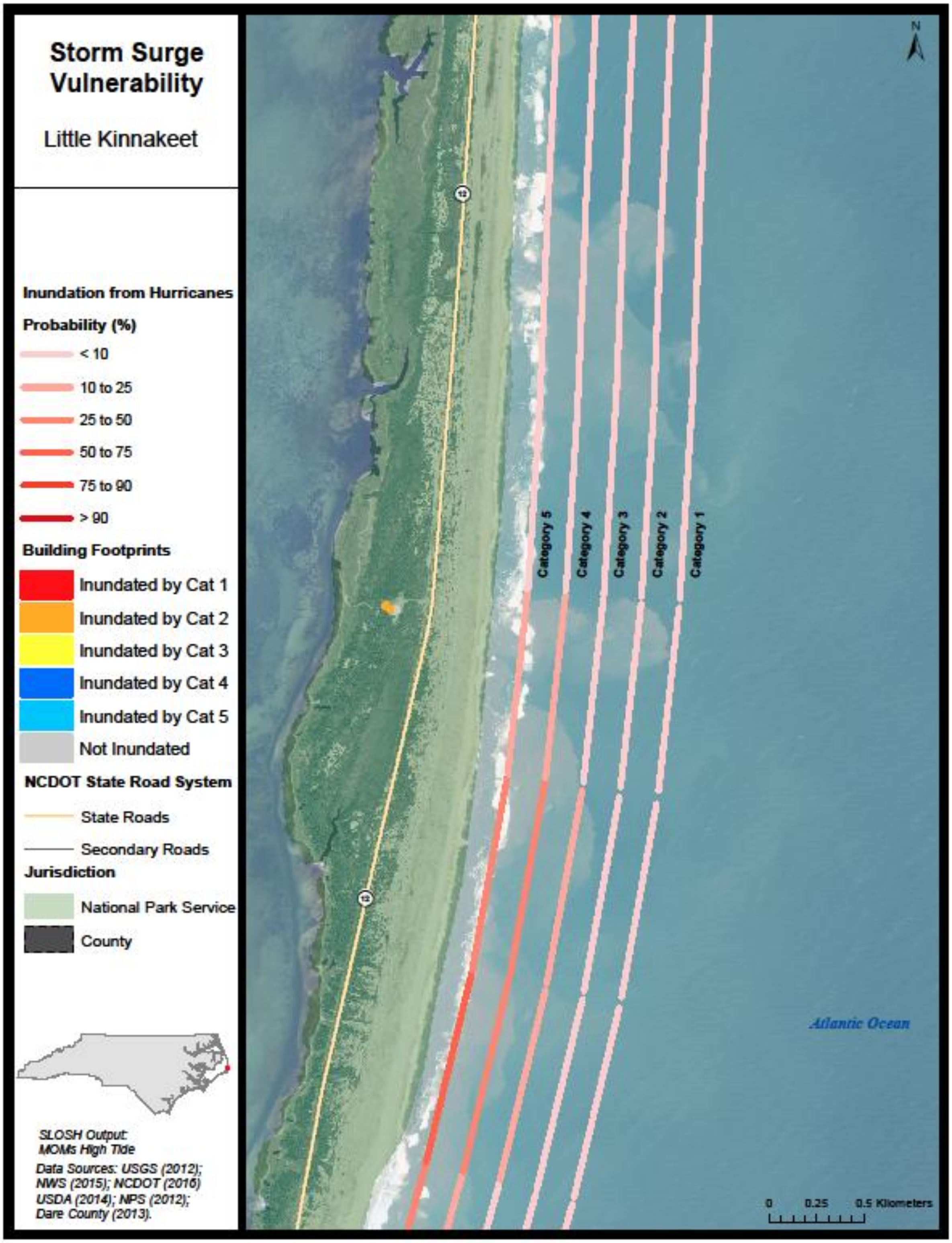

Potential Storm Surge +70cm SLR
Cape Hatteras National Seashore
Storm Surge Inundation
Category 1
Category 2
Category 3
Category 4
Category 5
NCDOT State Road System
U.S. Highways
State Roads
Secondary Roads
NCDOT Ferry Routes
Daily
Emergency
Jurisdiction
County
Storm surge inundation extent was determined by subtracting the SLOSH output (MOMs High Tide) from the 2014 NCFMP DEM.
Data Sources: NCFMP (2014) NWS (2015);NCDOT (2016); Dare County (2013); Hyde County (2009).
Albemarle Sound
Croatan Sound
Alligator River
Dare County
Hyde County
Pamlico Sound
Bodie Island Coast Guard Station
Bodie Island Light Station
Oregon Inlet
Pea Island National Wildlife Refuge
Little Kinnakeet Life Saving Station
U.S. Weather Bureau Station
Hatteras Island Light Station
Hatteras Inlet
Ocracoke Light Station
Ocracoke Inlet
Atlantic Ocean
N
0 2.5 5 10 Km

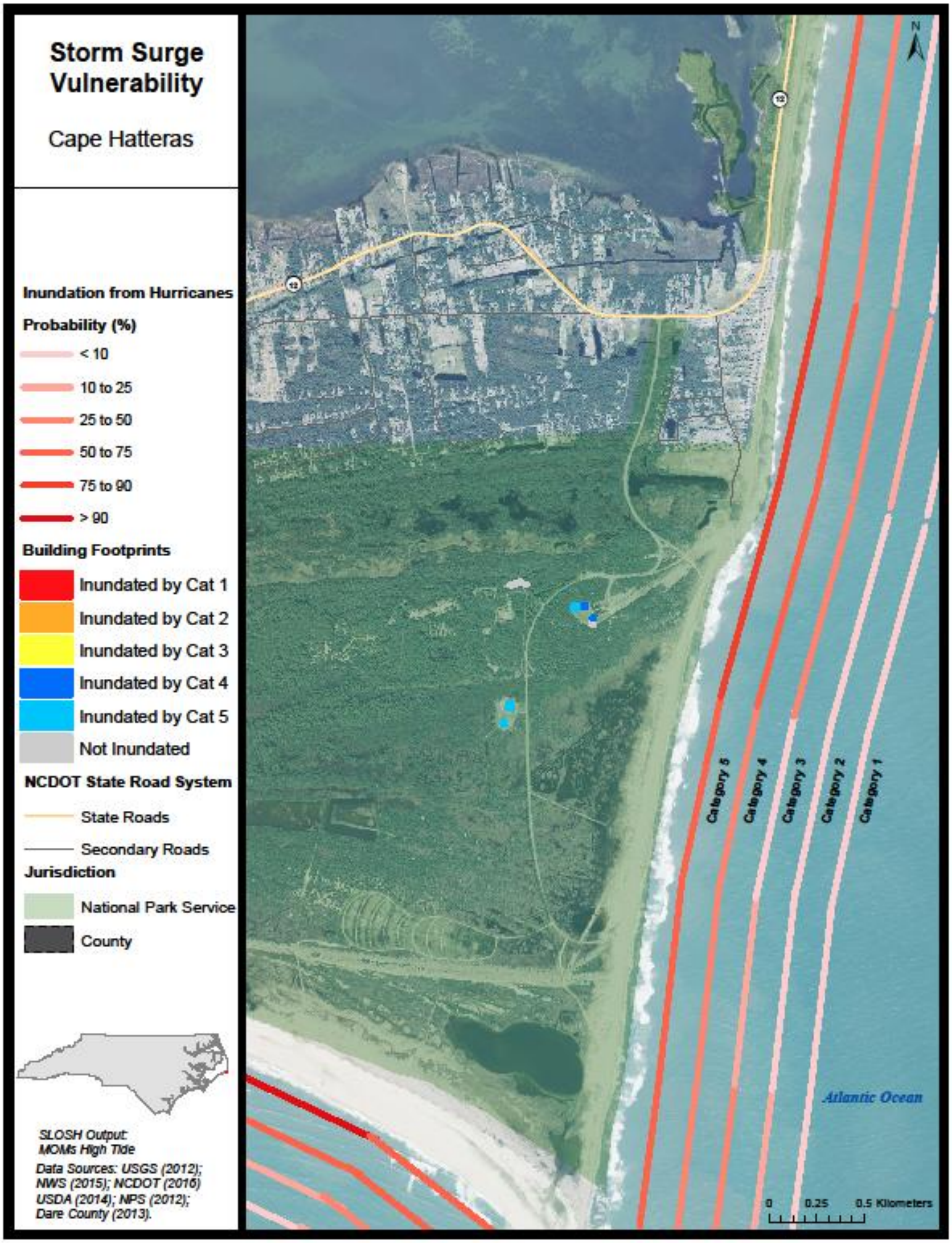

Potential Storm Surge +100cm SLR
Cape Hatteras National Seashore
Storm Surge Inundation
Category 1
Category 2
Category 3
Category 4
Category 5
NCDOT State Road System
U.S. Highways
State Roads
Secondary Roads
NCDOT Ferry Routes
Daily
Emergency
Jurisdiction
County
Storm surge inundation extent was determined by subtracting the SLOSH output (MOMs High Tide) from the 2014 NCFMP DEM.
Data Sources: NCFMP (2014) NWS (2015);NCDOT (2016); Dare County (2013); Hyde County (2009).
Albemarle Sound
Croatan Sound
Alligator River
Dare County
Hyde County
Pamlico Sound
Bodie Island Coast Guard Station
Bodie Island Light Station
Oregon Inlet
Pea Island National Wildlife Refuge
Little Kinnakeet Life Saving Station
U.S. Weather Bureau Station
Hatteras Island Light Station
Hatteras Inlet
Ocracoke Light Station
Ocracoke Inlet
Atlantic Ocean
N
0 2.5 5 10 Km

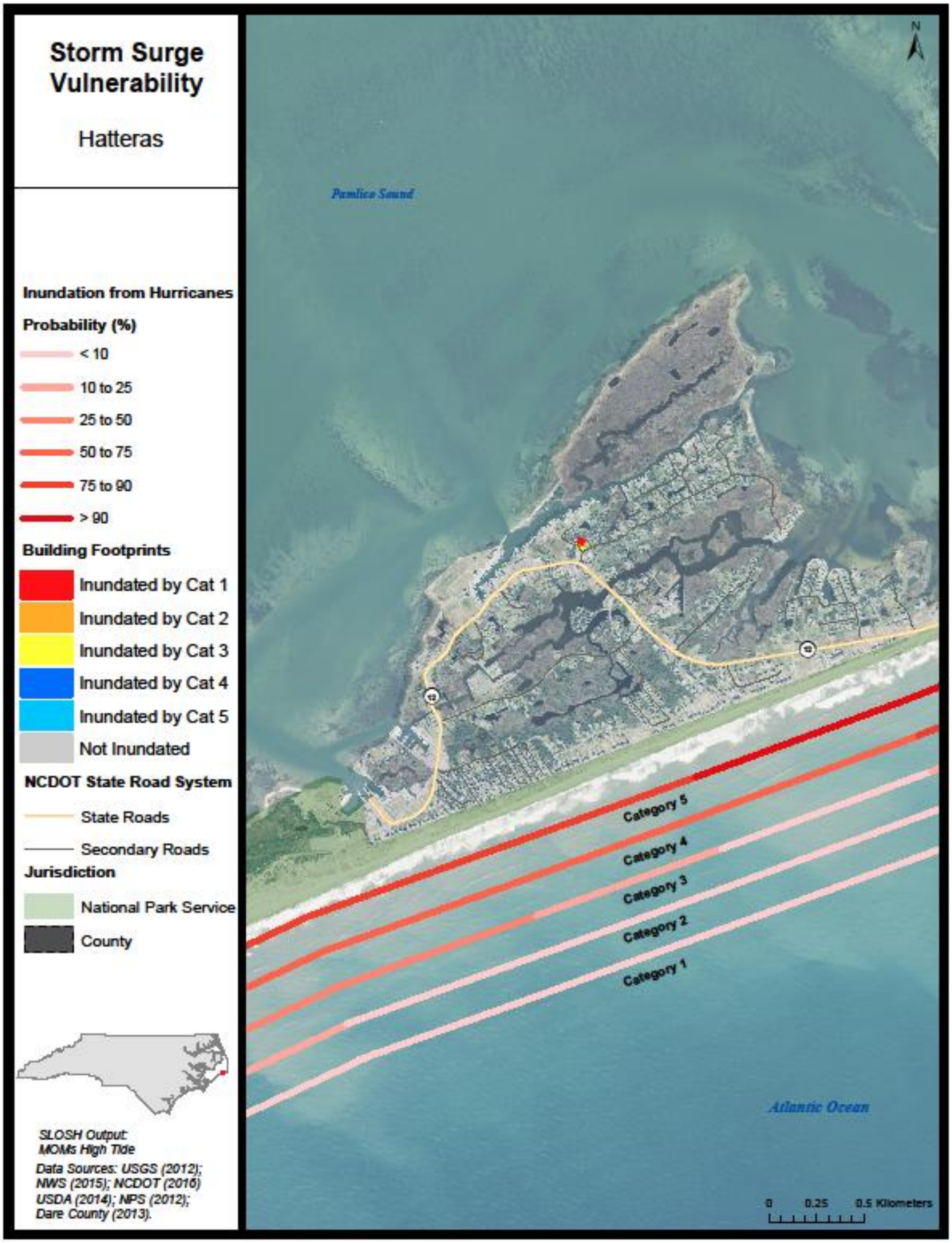

Potential
Storm Surge
+140cm SLR
Cape Hatteras
National Seashore
Storm Surge Inundation
Category 1
Category 2
Category 3
Category 4
Category 5
NCDOT State Road System
U.S. Highways
State Roads
Secondary Roads
NCDOT Ferry Routes
Daily
Emergency
Jurisdiction
County
Storm surge inundation extent was determined by subtracting the SLOSH output (MOMs High Tide) from the 2014 NCFMP DEM.
Data Sources: NCFMP (2014) NWS (2015);NCDOT (2016); Dare County (2013); Hyde County (2009).
Albemarle Sound
Croatan Sound
Alligator River
Dare County
Hyde County
Pamlico Sound
Bodie Island Coast Guard Station
Bodie Island Light Station
Oregon Inlet
Pea Island National Wildlife Refuge
Little Kinnakeet Life Saving Station
U.S. Weather Bureau Station
Hatteras Island Light Station
Hatteras Inlet
Atlantic Ocean
Ocracoke Light Station
Ocracoke Inlet
N
0 2.5 5 10 Km

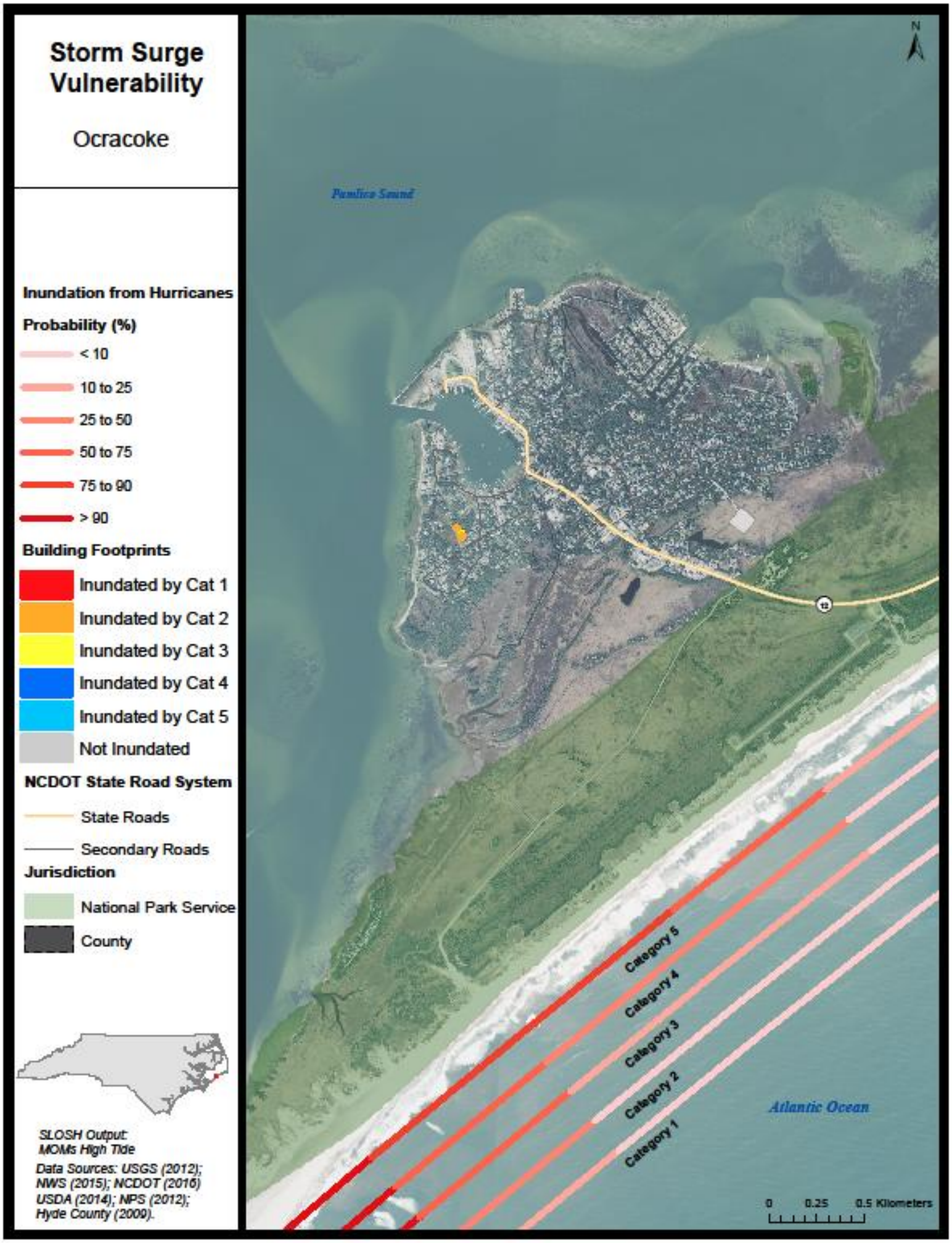
D. Storm Surge Inundation Risk by SLOSH MOM Category by District with CVI Inundation Probability



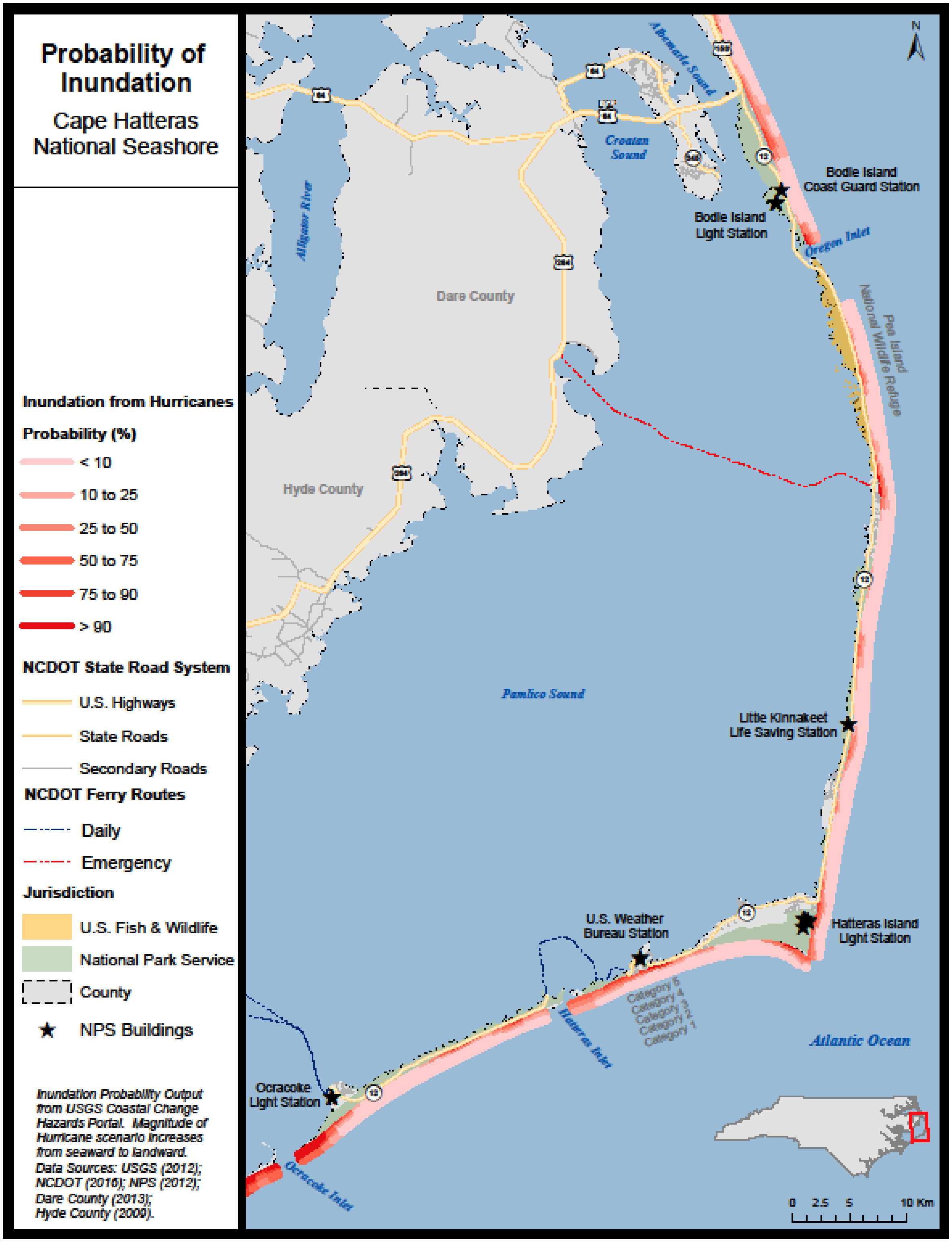

Storm Surge Vulnerability
Little Kinnakeet
Inundation from Hurricanes
Probability (%)
< 10
10 to 25
25 to 50
50 to 75
75 to 90
> 90
Building Footprints
Inundated by Cat 1
Inundated by Cat 2
Inundated by Cat 3
Inundated by Cat 4
Inundated by Cat 5
Not Inundated
NCDOT State Road System
State Roads
Secondary Roads
Jurisdiction
National Park Service
County
SLOSH Output:
MOMs High Tide
Data Sources: USGS (2012); NWS (2015); NCDOT (2016) USDA (2014); NPS (2012); Dare County (2013).
Category 5
Category 4
Category 3
Category 2
Category 1
Atlantic Ocean
0 0.25 0.5 Kilometers
N


Storm Surge Vulnerability
Cape Hatteras
Inundation from Hurricanes
Probability (%)
< 10
10 to 25
25 to 50
50 to 75
75 to 90
> 90
Building Footprints
Inundated by Cat 1
Inundated by Cat 2
Inundated by Cat 3
Inundated by Cat 4
Inundated by Cat 5
Not Inundated
NCDOT State Road System
State Roads
Secondary Roads
Jurisdiction
National Park Service
County
SLOSH Output:
MOMs High Tide
Data Sources: USGS (2012); NWS (2015); NCDOT (2016) USDA (2014); NPS (2012); Dare County (2013).
Category 5
Category 4
Category 3
Category 2
Category 1
Atlantic Ocean
0 0.25 0.5 Kilometers
N


Storm Surge Vulnerability
Hatteras
Inundation from Hurricanes
Probability (%)
< 10
10 to 25
25 to 50
50 to 75
75 to 90
> 90
Building Footprints
Inundated by Cat 1
Inundated by Cat 2
Inundated by Cat 3
Inundated by Cat 4
Inundated by Cat 5
Not Inundated
NCDOT State Road System
State Roads
Secondary Roads
Jurisdiction
National Park Service
County
SLOSH Output
MOMs High Tide
Data Sources: USGS (2012); NWS (2015); NCDOT (2016) USDA (2014); NPS (2012); Dare County (2013).
Pamlico Sound
Category 5
Category 4
Category 3
Category 2
Category 1
Atlantic Ocean
0 0.25 0.5 Kilometers
N


Storm Surge Vulnerability
Ocracoke
Inundation from Hurricanes
Probability (%)
< 10
10 to 25
25 to 50
50 to 75
75 to 90
> 90
Building Footprints
Inundated by Cat 1
Inundated by Cat 2
Inundated by Cat 3
Inundated by Cat 4
Inundated by Cat 5
Not Inundated
NCDOT State Road System
State Roads
Secondary Roads
Jurisdiction
National Park Service
County
SLOSH Output:
MOMs High Tide
Data Sources: USGS (2012); NWS (2015); NCDOT (2016) USDA (2014); NPS (2012); Hyde County (2009).
Pamlico Sound
Atlantic Ocean
Category 5
Category 4
Category 3
Category 2
Category 1
N
0 0.25 0.5 Kilometers

E. Inundation Probability by Hurricane in USGS Coastal Vulnerability Index (CVI)



F. Historic District Field Visits

A field visit with Laura Pickens introduced the team to sites for vulnerability assessment within the CAHA. The first stop on the visit was at the Bodie Island Lifesaving and Coast Guard Stations (Figure F1).

Figure F1. Bodie Island Coast Guard Station on the right and the Lifesaving Station on the right, looking towards Highway 12 from Bodie Lighthouse Road (Photograph taken March 29, 2014).

Waves from the estuarine side of the Bodie Island Historic District were reported to have swashed through the parking lot almost to the Light Keepers' Station (Figure F2) during Hurricane Irene in 2011. From the ground this region seemed appears sheltered, yet the 2012 NAIP DOQQ revealed the proximity to Roanoke Sound, Oregon Inlet, and the Atlantic Ocean (Figure F3).

Figure F2. Bodie Island Light Keepers' Station and, Oil House, and Lighthouse (Photograph taken March 29, 2012).

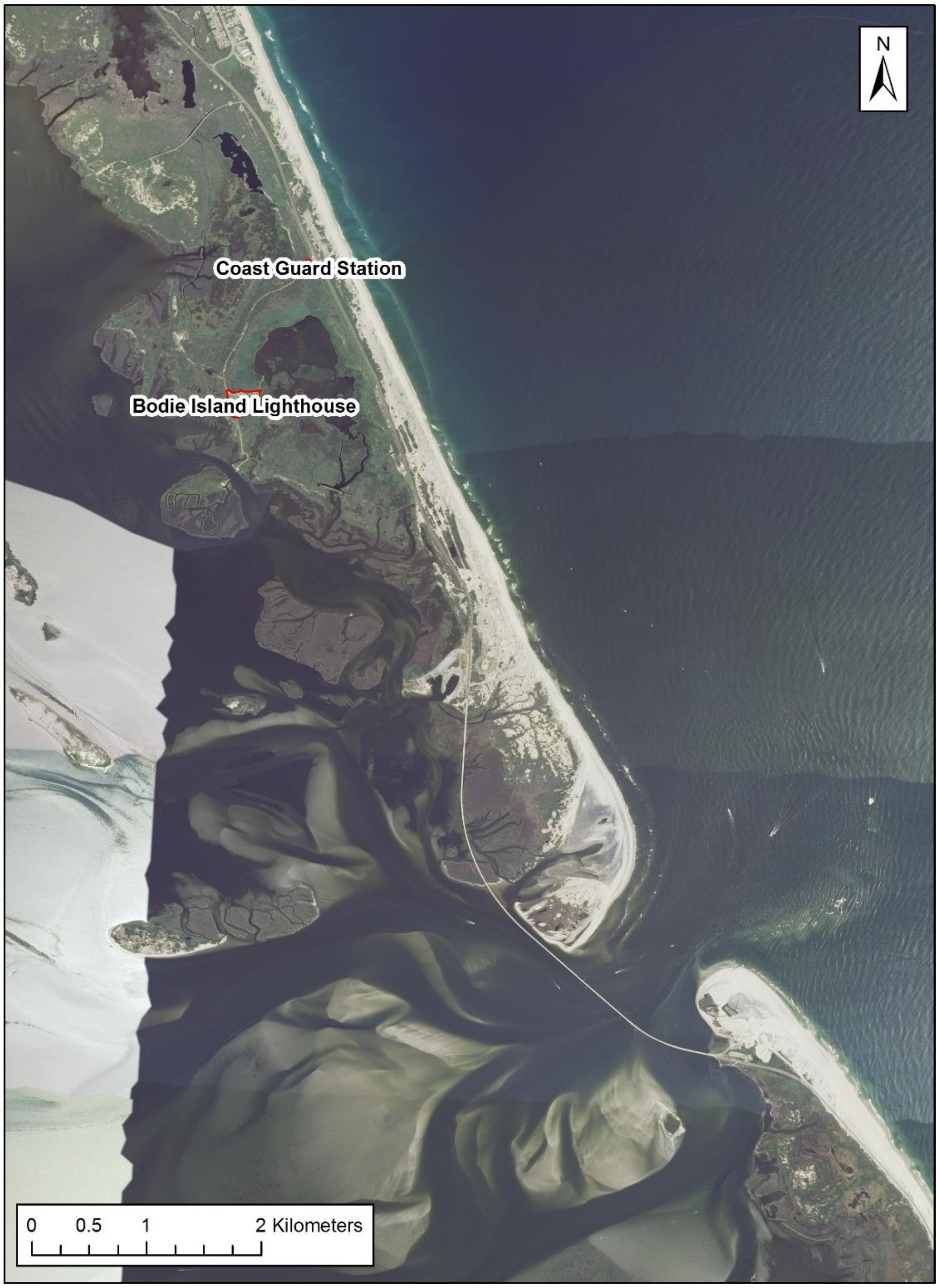


Figure F3. Aerial Imagery of Bodie Island Coast Guard Station and Lighthouse (NAIP DOQQ, 2012).

Little Kinnakeet Historic District was fenced off from the public and undergoing restorations. This historic district is located on the estuarine side along an undeveloped stretch between Salvo and Avon (Figure F4).

Figure F4. A) Aerial Imagery of Little Kinnakeet (NAIP DOQQ, 2012), B) Aerial imagery of Little Kinnakeet (Google Maps, 2014), C) Aerial imagery of Little Kinnakeet Historic District (Google Maps, 2014).

Cape Hatteras Lighthouse once stood at the site now marked by a ring of foundation stones (Figure F5). These granite foundation stones had the names of the keepers that once served the lighthouse engraved on them. Many of the original stones had been buried or relocated from the physical forces from Hurricane Sandy, and now formed a semi-circle known as the "Keepers of the Light Amphitheater."

Figure F5. Former location of the Cape Hatteras Lighthouse, which is now occupied by Foundation Stones that were placed there after the lighthouse was relocated in 1999 (Photograph taken March 29, 2014).

Figure F6. A) Aerial Imagery of Cape Hatteras Lighthouse, Ranger Station, and CCC Cabins (NAIP DOQQ, 2012), B) Looking from the foundation stones towards Cape Hatteras Light House (Photograph taken March 29, 2014), C) Relocated Cape Hatteras Lighthouse District (Photograph taken March 29, 2014).

The final visit was to the Cape Hatteras Weather Bureau, where we were greeted by the day's volunteer who told us that it was the second weather station in the United States built in 1874. The first coastal observation station was in Wilmington, NC established in 1871 (NPS, 2014).

Figure F7. Cape Hatteras Weather Bureau and storage sheds.

Figure F8. Aerial imagery of Weather Bureau located in Hatteras (NAIP DOQQs, 2012).