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HIGHLIGHTS

- Shoreline change analysis shows systemic and accelerating beach erosion.
- Erosion hotspots affect natural and cultural resources and pose chronic threats.
- Sea-level rise on the Seashore shows spatially variable future exposure from storm surge.
- Risk assessments inform hazard mitigation, adaptation, and relocation options.

ABSTRACT: *National seashores are cherished public lands with rich environmental, cultural, and historic resources. The Cape Hatteras National Seashore is one such coastal asset that is both bountiful yet vulnerable, with historic lighthouses, critical habitats, and recreational amenities alike facing threats of sea-level rise and continual storm and climate change impacts. Over 3 million visitors to the Seashore in 2021 set an annual visitation record. Historic resources such as the Bodie Island Lighthouse and Ocracoke Lighthouse are among the most visited sites, yet these assets are also among those most vulnerable to flooding, compromised structural integrity, and reduced accessibility. Future challenges to the protection and management of such resources are already being felt in the form of storms, extreme rainfall, and recurrent compound flooding. Such threats are also coincident with increasing visitation and recreational demand. This paper examines the science-based data that are being collected and management efforts underway to inform future planning, intervention, or adaptation to sea-level rise and barrier island evolution. The paper identifies the opportunities for mitigation and adaptation as well as potential environmental tipping points and limits to resilience by assessing the frequency and magnitude of flooding events and shoreline change.*

KEYWORDS: Shoreline change, Coastal hazards, Sea-level rise, National seashore, Outer Banks

INTRODUCTION

Among protected areas of the southeastern United States, few areas rival the public's affection for natural scenic beauty and recreation as its national seashores. These protected and public lands contain a wealth of natural and cultural resources yet are emblematic of the growing threats of climate change, rising sea level, creeping coastal development, and mass tourism. Coastal erosion has increased the vulnerability of properties to storm damage and left others uninhabitable. Projections of sea-level rise, changing storminess, and accompanying climate change effects may drive responses of beaches and dunes to rates far exceeding historical records. The shifting Atlantic Meridional Oscillation may alter storm tracks in the southeastern United States between hotspots in the Gulf of Mexico and those in North Carolina (Keim and Muller 2007).

The geophysical setting of some seashores also exacerbates the threat of sea-level rise (SLR), including faster subsidence rates owing to the relaxation of a glacial forebulge, groundwater extraction, and agricultural ditching and drainage. Some areas of the Southeast, such as Brunswick, Georgia, are disproportionately socially vulnerable to SLR (Spears 2021), and others note the increasing vulnerability of coastal habitats, such as those of Cumberland Island National Seashore (Peek et al. 2016). National seashore managers are responsible for maintaining diverse assets that support visitors and natural resources in the public trust across large swaths of the Southeast. In addition to provisioning tourism and recreational assets such as parking lots, visitor centers, restrooms, and roads, park managers and staff are also stewards of natural resources that are dynamically responding to sea level, storms, and the effects of climate change. For the Cape Hatteras National Seashore of North Carolina's Outer Banks, these natural resources include wildlife (resident and migratory as well as threatened and endangered species), critical habitats, and cultural and historical resources such as shipwrecks, historic properties, and national monuments such as the Bodie Island, Cape Hatteras, and Ocracoke lighthouses.

Sea-level rise research on the Outer Banks has a rich history itself, including studies that extend basic research to provide assessments for adaptation planning, such as Titus and Wang (2008) and the *NC Sea Level Rise Risk Management Study* (*NC-SLRRMS*) (North Carolina Division of Emergency Management 2012). Titus and Wang (2008) implemented an analysis of regional vulnerability, although their study was conducted at a coarse regional scale. The *NC-SLRRMS* sought to evaluate flood zones and potential damage from flood events and, as such, focused on modeling floodplains. Neither study undertook assessment or integration of multiple hazards and vulnerabilities nor used fine spatial resolution to focus on historic cultural sites and structures and natural resources. However, those studies' baseline data motivated this study to provide actionable information for resource management. The *NC-SLRRMS* assimilated data sources and process rate measurements for a pilot study on the Outer Banks to verify robustness of inundation modeling methods. Gore (2012) focused narrowly on the mainland of Dare County at the Alligator River National Wildlife Refuge and the nearby Pea Island

National Wildlife Refuge to assess the error, uncertainty, and sensitivity of the Sea Level Affecting Marshes Model (SLAMM) used in the methodology of the *SLRRMS*. Along with erosion rates from long-term shoreline mapping by the NC Division of Coastal Management (NCDCM) (NCDCM 2019) and several studies evaluating the subsidence and relative sea level across the region (NCCRC 2016), these prior studies provided data and a process-based foundation for the vulnerability assessment herein.

The U.S. National Park Service (NPS) has undertaken system-wide risk assessments and planning for seashores and other NPS units exposed to SLR (Caffrey and Beavers 2008, 2013). The U.S. Geological Survey (USGS) created a coastal vulnerability index (CVI) and the Coastal Change Hazards Portal that considers shoreline change and morphological factors for parks to use in early risk assessments (Thieler and Hammar-Klose 1999, USGS 2022). The *Digital Coast* geospatial portal, maintained by the National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management (OCM), provides federated digital data to study and update changes in shorelines and 3D morphology of beaches and dunes (NOAA 2022). The NOAA National Geodetic Survey (NGS) has regularly flown post-storm imagery, LiDAR, and 3D Digital Surface Models after storms, providing multi-temporal datasets for long- and short-term response studies. The US Coastal Research Program (USCRP) led the *DU*ring *N*earshore *E*vent e*X*periment (DUNEX) study on the Outer Banks to advance scientific approaches to studying rapidly changing beach and barrier island morphology (USCRP 2022). The NPS has found utility in these projects to address specific threats, such as tidal flooding, coastal erosion, and storm surges. Assessments have also been conducted with a focus on archeological resources (e.g., Jamestown, Colonial Williamsburg, and Yorktown National Battlefield), cultural heritage and historic landmarks (e.g., the Cape Hatteras Light Station), and capital infrastructures such as streets, parking lots, bath houses, and utilities.

Scope and Objectives

To advance the use of coastal science and geospatial analysis in national seashore management, this paper presents an assessment of coastal risks from dynamic barrier island shoreline changes, storm surges, and future sea-level rise at the Cape Hatteras National Seashore (Seashore) on the Outer Banks of North Carolina. A multi-hazard approach allows for short- and long-term potential adaptations. The study focuses on long-term shoreline change analysis, potential storm surges with future SLR, and developing geospatial datasets for exposure assessments for cultural and natural resources and infrastructure. Relevant data, rates of change, and near-term projections of conditions from years to decades are also presented. Results could provide the NPS with potential mitigation options, identify the most critical vulnerabilities and uncertainties, and inform seashore capital project planning.

Study Area

The Cape Hatteras National Seashore was established in 1937 to preserve cultural and natural resources of national significance. The enabling legislation for the Seashore, the Code of Federal Regulations 36 CFR parts 1–199, and the Park Compendium provide guidance on how the park can be managed by the National Park Service (Binkley 2007, NPS 2022a). The Seashore shares boundaries with counties and towns and coordinates management with federal and state agencies including the U.S. Fish and Wildlife Service (USFWS), which oversees the management of the Pea Island National Wildlife Refuge (PINWR), and the NC Department of Transportation (NCDOT). The establishment of these jurisdictions has influenced where coastal development has occurred as well as the regulations that have guided resource management, conservation, visitor use, recreation, and tourism throughout the region. Therefore, it is important to implement effective hazard mitigation planning to reduce both the short- and long-term risks that coastal hazards pose to the park's historic, cultural, and natural resources.

The boundary of the Seashore is the extent of the study area (Figure 1). The northern boundary is located at "Whalebone Junction" in Nags Head, NC, then extends south along Bodie Island to its terminus where the Marc Basnight Bridge carries vehicle traffic across Oregon Inlet to Hatteras Island. Hatteras Island is the longest barrier island (~87 km) of the Outer Banks and separates the Atlantic Ocean from the Albemarle-Pamlico Estuarine System, the second largest estuary in the United States after the Chesapeake Bay. The northern 20 km of Hatteras Island is managed by the USFWS as the Pea Island National Wildlife Refuge. Seven unincorporated villages are intermixed with undeveloped stretches between the Oregon and Hatteras inlets, with narrow ~1 km to 0.2 km island widths except for Cape Hatteras. 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. Across Hatteras Inlet, Ocracoke Island extends the Seashore for 25 km to the southwest, with island widths ranging from 150 m at the north end of the island to 2.8 km at Ocracoke Village. Access to Ocracoke Island is possible via ferries operated by the NCDOT Ferry Division from Hatteras Island and mainland Cedar Island and Swan Quarter. A seasonal fee–based passenger ferry service route from Hatteras Village to Silver Lake Harbor in Ocracoke Village was introduced in May of 2019.

For the Outer Banks, access to Hatteras and Ocracoke Island by tourists and residents is largely provided by NC Highway 12 (NC 12). Transportation along this highway has been interrupted on many occasions by hurricanes (Isabel [2003], Irene [2011], Sandy [2012], Dorian [2019]) and nor'easters. The management of this transportation corridor is complicated by diverse stakeholder interests, including federal and state agencies, as well as local residents. The re-opening of the historic 1933 "New Inlet" during Hurricane Irene (2011) led the NC Department of Transportation (NCDOT) to construct an overpass at this segment of the PINWR. The NCDOT also developed a plan for the "Jug Handle" bridge, which now bypasses the overwash-prone area along the southern PINWR via causeway into the village of Rodanthe. This bridge opened just months ahead of large swells from offshore Hurricane Earl in September of 2022 that would have closed NC 12 due to a major overwash at the section of highway the bridge now bypasses.

The long-term viability of the NC 12 transportation corridor has attracted intense scrutiny, planning, and public controversy over the past several decades due to periodic

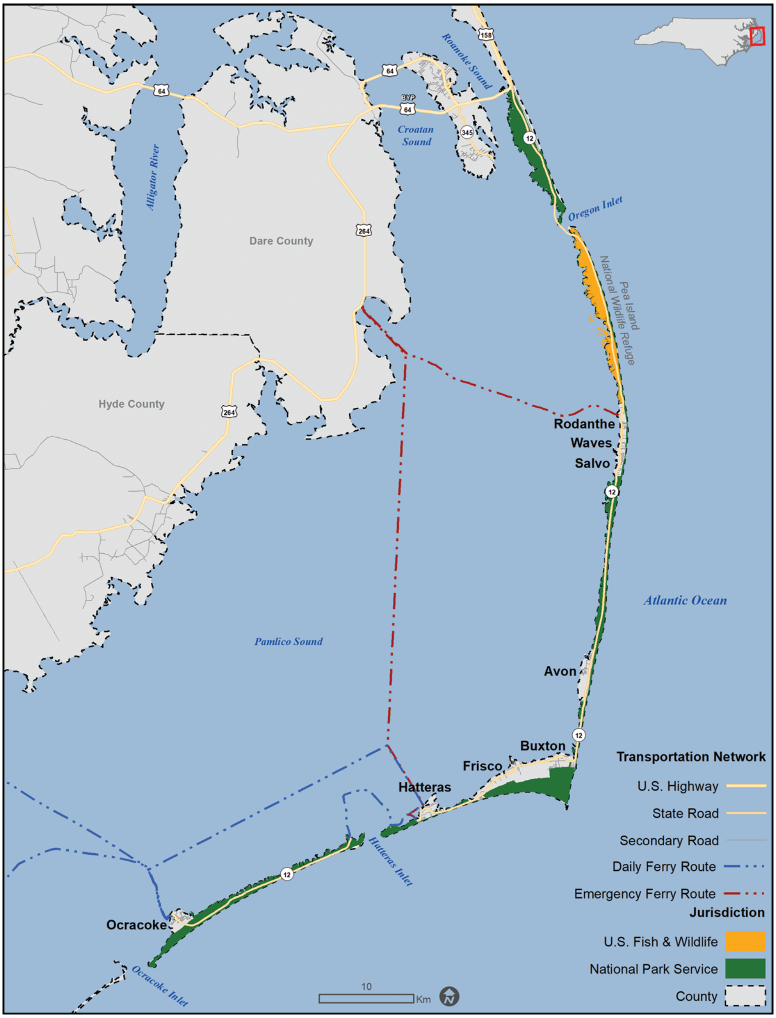

Figure 1. Study area location, the Cape Hatteras National Seashore, Outer Banks of North Carolina.

disruptions along areas vulnerable to ocean overwash and continued coastal erosion, which threaten the structural integrity of the highway. Potential inlet opening, such as the 2003 Isabel Inlet "breach" between Frisco and Hatteras villages, has profound implications for vehicular access, commerce, and recreation. Some vulnerable areas include: a) the "Canal Zone" at the northern tip of Hatteras Island near Oregon Inlet; b) the Pea Island National Wildlife Refuge Visitor Center; c) the Rodanthe *S*-Curves along NC 12 and Mirlo Beach; d) land south of the village of Avon; e) the "Haulover" site just north of Buxton; f) Sandy Bay between Frisco and Hatteras villages; and g) northern Ocracoke Island, near the South Dock ferry terminal.

Heavy equipment is routinely used by the NCDOT to manage the highway because of continued oceanfront shoreline erosion, aeolian deposition, and overwash during storm events. The Rodanthe *S*-Curves derived its moniker from the landward relocation of a section of NC 12 to accommodate the historical erosion, giving the route a curvilinear feature. The installation of large 4.5 m sandbags along sections of NC 12 in 2012 (North Carolina Department of Transportation 2012) and a beach nourishment project in 2014 were measures to protect the structural integrity of the highway until the highly vulnerable stretch of highway could be relocated to the Rodanthe Bridge, which runs over the Pamlico Sound and bypasses this section of barrier island entirely, in 2022. Beach nourishment remains the prevailing strategy to mitigate coastal hazards that disrupt travel along NC 12 in the southern Avon and Haulover/Buxton areas. Projects in the summer of 2022 were conducted simultaneously along stretches of oceanfront in both areas, and a standalone nourishment project was completed along Haulover/Buxton for the first time in 2017–2018. Sandy Bay, the narrow undeveloped area between the villages of Frisco and Hatteras, was breached during Hurricane Isabel (2003) and remains as a section of Hatteras Island with minimal width and elevation. The north end of Ocracoke Island was breached during Hurricane Dorian (2019) and sandbags were placed along the oceanfront to protect NC 12 after it was repaired. However, continued landward migration of the shoreline threatens the viability of this stretch of highway and the NCDOT has initiated studies to evaluate the feasibility of relocating the South Dock ferry terminal to locations that would bypass this vulnerable section of highway.

METHODS

Calculating Oceanfront Shoreline Change Rates

The Digital Shoreline Analysis System (DSAS), developed by the U.S. Geological Survey (USGS), is a freely available software application that works within ESRI's desktop Geographic Information System (ArcGIS) software (Dolan et al. 1991, Himmelstoss et al. 2018a). Historical oceanfront shoreline positions representing the location of the high water line (HWL) between 1998 and 2022 were compiled and imported into a geodatabase for use with DSAS v5.1 (Table 1). The historical shoreline position data were either delineated from aerial imagery via wet-dry interpretation and digitized at the 1:1,000 scale by NCDCM staff (NCDCM 2019), delineated from field surveys of wet-dry interpretation collected with survey-grade global navigation satellite system (GNSS) units then post-processed by NPS staff (Baron 2018), or delineated from high-resolution satellite imagery at the 1:2,400 scale by NPS staff for the purpose of providing coverage along the PINWR to supplement NPS field mapping efforts.

Uncertainty of shoreline data was ascribed from the self-reported accuracy standards in the respective data sets. For instance, the NC Division of Coastal Management implements a standardized digitizing procedure for the wet/dry line that inherits the spatial positional accuracy of the source imagery (see methods report NCDCM 2019 and Baron 2018). Aerial photography missions follow a prescribed collection and accuracy

Table 1. Aerial, satellite, and field survey data sources and extents (the Cape Hatteras National Seashore, CAHA, and Pea Island National Wildlife Refuge, PINWR) for oceanfront shoreline data used to calculate shoreline change rates and estimate future ten- and twenty-year shoreline position.

Date	Uncertainty (m)	Extent	Source
7/22–8/18/1998	2.0	CAHA	NCDCM Aerial Imagery
2/1/2022	1.0	CAHA	Dare County Aerial Imagery
9/3/2004	1.0	CAHA	NCDCM Aerial Imagery
2/24/2006	1.0	CAHA	Hyde County Aerial Imagery
3/3/2007	1.0	CAHA	Dare County Aerial Imagery
7/11/2009	1.7	CAHA	USDA National Agriculture Imagery Program
4/11/2010	1.0	CAHA	NC 911 Aerial Imagery
2/28/2012	1.0	CAHA	NC Aerial Imagery
1/30/2016	1.0	CAHA	NC Aerial Imagery
3/27–27/2017	5.0	CAHA	NPS GNSS Mapping
4/21–26/2018	5.0	CAHA	NPS GNSS Mapping
10/20–24/2018	5.0	CAHA	NPS GNSS Mapping
3/28–31/2019	5.0	CAHA	NPS GNSS Mapping
9/12–16/2019	5.0	CAHA	NPS GNSS Mapping
1/1/2020	1.0	CAHA	NC Aerial Imagery
7/25/2020	5.0	PINWR	Satellite Imagery (WorldView 2)
11/03–6/2020	5.0	CAHA	NPS GNSS Mapping
4/14/2021	5.0	PINWR	Satellite Imagery (WorldView 2)
4/19–22/2021	5.0	CAHA	NPS GNSS Mapping
3/3/2022	5.0	PINWR	Satellite Imagery (WorldView 3)
3/23–26/2022	5.0	CAHA	NPS GNSS Mapping

standard and spatial resolution. Uncertainty estimates are meant to capture a variety of sources of potential error, such as tidal anomalies or seasonal solunar variations (e.g., spring and neap tides) and seasonal differences in shoreline location as a function of beach dynamics (e.g., winter vs. spring profiles). The uncertainty measures chosen are greater than the spatial resolution of the source imagery, which reflects error in the digitization of a shoreline sub-pixel resolution as well as spatial positional error (i.e., root-mean square error or RMSE).

Implementing the DSAS methodology, a digital baseline was constructed as a new feature class in the geodatabase and transects were cast offshore following the DSAS workflow. The transects were cast orthogonal to the baseline using 10 m spacing and a user-specified smoothing distance of 500 m to account for some of the curvilinear sections of shoreline near the inlets and Cape Hatteras. DSAS v5.1 was then used to calculate the following statistics: shoreline change envelope (SCE), net shoreline movement (NSM), end point rate (EPR), linear regression rate (LRR), and weighted linear regression (WLR) (Himmelstoss et al. 2018b). The uncertainty of calculated rates of change depends on the combined positional uncertainty associated with field survey measurement and digitizing uncertainties derived from the source imagery (Ruggiero et al. 2013).

Future Ten- and Twenty-Year Shoreline Positions

Given the need to inform long-range planning for infrastructure, cultural landmarks, and ecological resources on the shore, we sought a reliable, first-order estimate of future shoreline locations relying principally on historic shoreline change rates. Long and Plant (2012) developed a methodology for forecasting shoreline evolution using an extended Kalman filter framework (Kalman 1960). The latest DSAS software version 5.1 includes an experimental shoreline forecasting model able to generate ten- and twenty-year future shoreline horizons and uncertainty bands in addition to being able to calculate the statistics used in this study (Himmelstoss et al. 2018b). The LRR is the shoreline statistic that must be generated to initialize the Kalman filter model (Himmelstoss et al. 2018b). The percentage of variance in the data that is explained by regression is represented by the R-squared statistic (R^2), or the coefficient of determination (Himmelstoss et al. 2018b). Acknowledging the assumptions inherent to future extrapolation of shoreline change rates, this approach is justifiable as a first-order estimate of long-term average changes. Careful consideration of the local beach and shoreface sediment budget, lithology, and dependency on human interventions (sandbags, replenishment, bulldozing dunes back into place after overwash, and sand fencing) all prompt assumptions that such interventions may be continued to sustain the beach-dune morphology. Physical processes and dynamics must also be assumed somewhat consistent and critically assessed, including the steepness of the upper shoreface, rate of longshore transport, offshore distance to depth of closure, and decadal trends in storm tracks and general storminess. Provided an ample quantity of long-term shoreline data and a critical measure of uncertainty for the source spatial accuracy and precision, future ten- and twenty-year potential shoreline positions (and an envelope of uncertainty) are desirable and reasonable products for resource management (Flynn and Hallac 2021).

Modeling Storm Surge Inundation

Storm surge analysis was conducted to assess the current and future exposure of assets to flooding. The approach relied heavily on the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) operational surge model and digital elevation models (DEMs). Allen et al. (2017) used the coastal inundation mapping methodology developed by NOAA (2015) to evaluate the vulnerability of historic structures located within the Seashore to storm surge and sea-level rise. Storm surge modeling data were obtained from the SLOSH display program and used to map the extent of inundation for each model scenario. The SLOSH model was developed by the National Weather Service (NWS) to "estimate storm surge heights, resulting from historical, hypothetical, or predicted hurricanes by taking into account the atmospheric pressure, size, forward speed, and track data" (NHC 2020).

There are three modeling approaches that can be used to estimate storm surge: deterministic, probabilistic, or composite. The deterministic approach performs a single simulation based on a hurricane forecast. The probabilistic approach, or P-Surge, performs ensemble model runs based on forecast error. There are actually two variants of the composite approach, the Maximum Envelope of Water (MEOW) and the Maximum of the MEOWs (MOMs), "which are regarded by the National Hurricane Center (NHC) as the best approach for determining storm surge vulnerability for an area since it takes into account forecast uncertainty" (NHC 2020). The MEOWs are composite products that are 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 surge value that was calculated for a particular grid cell is assigned. The 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. Allen et al. (2017) used the water level data from the MOMs for Category 1 – 5 storms occurring at high tide for inundation mapping purposes to assist the NPS staff with mitigation planning under worst case scenarios since previous studies (Sheng et al. 2010, Riggs et al. 2011, Clinch et al. 2012, Barnes 2013, Mulligan et al. 2014) illustrated the variability of storm surge and geomorphic response to different storm events.

Determining the depth of inundation that would occur under each model scenario requires subtracting the value of the water level from the value of the topographic and bathymetric data representing the elevation at a given location within the study area. The uncertainty of the elevation data used for inundation studies is critical to the reliability of the results (Gesch 2018). Allen et al. (2017) generated a DEM of the study area from Quality Level 2 bare earth LiDAR data that were collected for the North Carolina Floodplain Mapping Program in 2014. The vulnerability of historic structures standing within the Seashore to storm surge was then evaluated by subtracting the first-floor elevation (FFE) from the value representing the depth of inundation at the location of the structure for each scenario to determine if the water level exceeded the FFE. Given that most structures have a foundation or pilings elevating them above ground level, this "freeboard" vertical height and the FFE give a reasonable approximation of the height at which building damage would significantly increase. The FFEs for the park structures were obtained in 2022 by NPS staff using survey-grade GNSS units.

Evaluating the Effect of Relative Sea-Level Rise

Risk assessment of park structural assets to sea-level rise was initially investigated by Allen et al. (2017) and included simulated storm surge heights that would occur under relative sea-level rise scenarios of 20, 40, 70, 100, and 140 cm. This approach helped to identify areas within the seashore that are less vulnerable for the purpose of considering the possibility of relocating historic structures to safer locations. Relative sea-level rise (RSLR) was chosen to account not only for steric elevation of the coastal ocean and sounds, but also to factor the vertical land motion or subsidence in the region. These rates were estimated from the long-term available tide gauge records between the U.S. Army Corps of Engineers' Field Research Station in Duck, NC, and newer gauges at Oregon Inlet and in Beaufort, NC (NCCRC 2016). For the period of study from the present to the future approximately fifty-year period, we chose to adopt a morphostatic landform state, without extreme, low-probability events such as barrier island collapse or major, multiple new inlet opening events. The caveat of using a morphostatic landform to evaluate the effect of sea-level rise over a fifty-year timeframe was addressed by acknowledging the complexity of effort required to model a morphodynamic landform responses in a coupled human-natural system that is notably complex and non-linear along coastal barriers, spits, and cape complexes (cf. Allen et al. 2012). In addition, the vertical accuracy of the topographic and bathymetric elevation data is a limiting factor for mapping minimum sea-level rise scenarios, as addressed by Allen et al. (2017).

RESULTS

Historic Oceanfront Shoreline Change Results

Analyzing the net shoreline movement statistic provides a general understanding of the morphological evolution along the oceanfront of the Seashore between 1998–2022. Table 2 summarizes the shoreline change rate statistics. Complementing these statistics and providing spatial patterns and variability, Figure 2 portrays these changes using the linear regression rate (LRR) for the entire oceanfront of the Seashore.

Seven distinct hotspots are discernable on the map of shoreline change rates, with moderate to high rates of change in Table 2 (negative values indicate landward movement, or recessional and erosional change in the shoreline position). For instance, during this period the shoreline along Bodie Island migrated landward with distances generally increasing from north to south from ramps 1–4 of the off-road vehicle route that generally parallels NC 12. The shoreline position just to the south of Ramp 4 was relatively stable and acted like a hinge point before the shoreline migrated landward at greater distances towards the southern terminus of Bodie Island with proximity to Oregon Inlet.

The region immediately south of the terminal groin on the north end of Pea Island migrated seaward before a shift in landward movement occurred near the Canal Zone continuing to the PINWR Visitor Center until minimal seaward movement occurred at a local surf break known as "long walks." The relative stability transitioned to landward movement once again at Rodanthe *S*-Curves and continued in that direction until the village of Salvo. Relatively stable or seaward movement is observed from Salvo until Ramp 23. Afterwards, the shoreline movement is generally landward until Ramp 34. Seaward movement is displayed from Ramp 34 to north of the Avon Pier. Dramatic landward movement south of the Avon Pier until Ramp 38 follows. Relative stability in the shoreline position is observed from Ramp 38 until the southern extent of Haulover. The oceanfront along the Haulover/Buxton area experienced landward movement

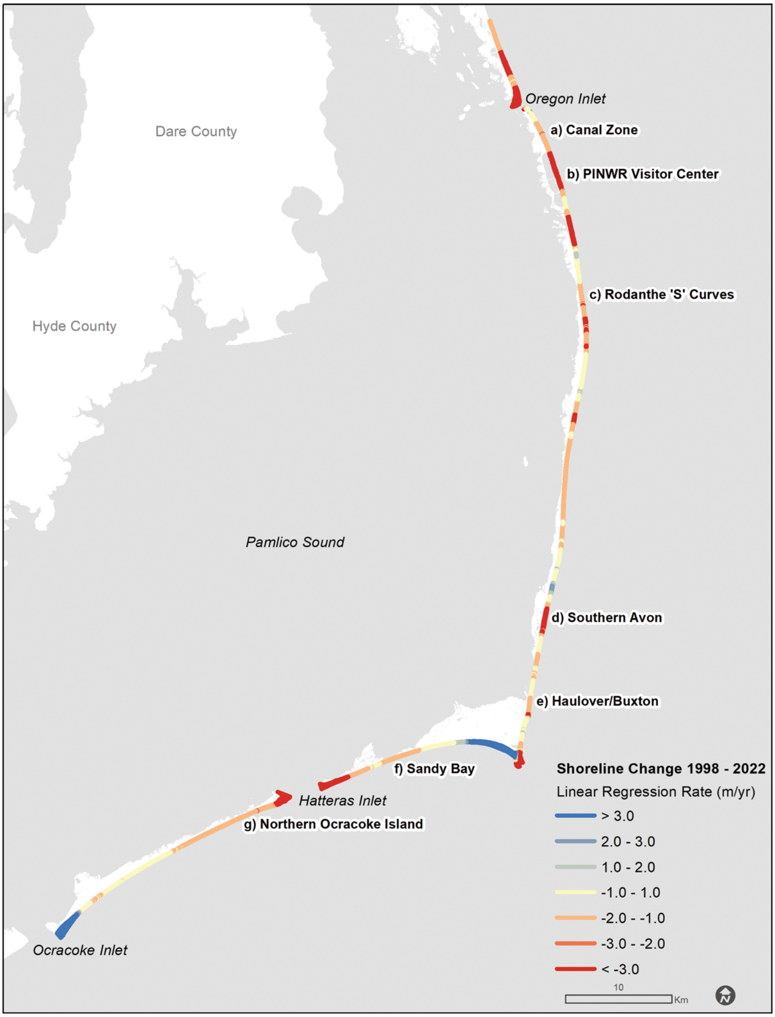

Figure 2. Results of oceanfront shoreline change rates along the Cape Hatteras National Seashore between 1998–2022 with references to the NC 12 erosion hotspots.

of the shoreline position. Then the shoreline holds a more stable position beginning from the first of three terminal groins that were originally installed to protect the Cape Hatteras Lighthouse and continues to Ramp 43.

Cape Hatteras has regularly undulated its orientation between north and south and varied in total area. However, since 2017 a reduction in beach area over time has been observed with landward migration of the northern shoreline position near Ramp 44. The southern shoreline position along the area known as South Beach has continued to migrate seaward each year at decreasing distances towards Ramp 48 and eventually

Table 2. Shoreline change statistics calculated from oceanfront shoreline positions along the Cape Hatteras National Seashore between 1998–2022 summarized for each NC 12 erosion hotspot and the total length of the Seashore.

Location		Net Shoreline Movement (m)			Linear Regression Rate (m/yr.)		
		Mean	Min	Max	Mean	Min	Max
NC12 Hotspot	Canal Zone	-28.34	-49.60	10.85	-2.45	-3.22	-1.50
	Pea Island Visitor Center	-86.73	-106.15	-56.33	-4.27	-4.75	-3.88
	Rodanthe *S*-Curves	-60.46	-90.41	-23.76	-2.26	-3.1	-1.29
	Southern Avon	-92.74	-113.88	-65.79	-4.51	-5.2	-3.34
	Haulover/Buxton	-34.01	-76.16	-2.35	-1.44	-2.86	-0.32
	Sandy Bay	-36.89	-54.07	-24.45	-1.73	-2.24	-1.07
	Northern Ocracoke Island	-42.47	-61.54	-18.58	-1.79	-2.27	-1.21
	Cape Hatteras National Seashore	-22.65	-1134.61	550.24	-1.25	-38.12	18.80

holding a more stable position near Ramp 49. General landward movement at increasing distances extends from Ramp 49 to the southern terminus of Hatteras Island.

The north end of Ocracoke Island has migrated landward at greater distances in proximity to Hatteras Inlet. Landward movement continues from Ramp 59 to north of Ramp 67 before shifting to a more stable position between ramps 67–72. South Point, which is located south of Ramp 72 until the southern terminus of Ocracoke Island, has continued to migrate seaward in a similar fashion as South Beach.

Predicted Future Ten- and Twenty-Year Shoreline Positions

Results of the DSAS future shoreline predictions (Figure 3) portray expected landward forecast locations. The proximity of the future shoreline to NC 12 is extremely close along northern Pea Island, Sandy Bay, and stretches along northern Ocracoke Island. At these locations, a sediment deficit and erosional beach and increasingly fragmented dunes (bulldozed and sandbagged back into place after storms) show a growing threat to the highway at its present location. In contrast, some portions of NC 12 remain beyond the predicted future shoreline (and outside the envelope of uncertainty), such as the *S*-curves (where NC 12 has been diverted to Rodanthe via a new elevated causeway) and segments of Avon, Buxton and Hatteras villages where the road is set back onto the back-barrier and/or protected by large (albeit artificial) dunes.

Modeled Storm Surge Inundation

The results of the storm surge inundation analysis emphasize the need for attention to identify strategies to mitigate, adapt, or relocate assets due to their current flooding exposure. The results were evaluated for the cultural and historic structures located at the Bodie Island and Ocracoke light stations and indicate that even storm surge generated from a Category 1 hurricane scenario occurring at high tide poses a concerning

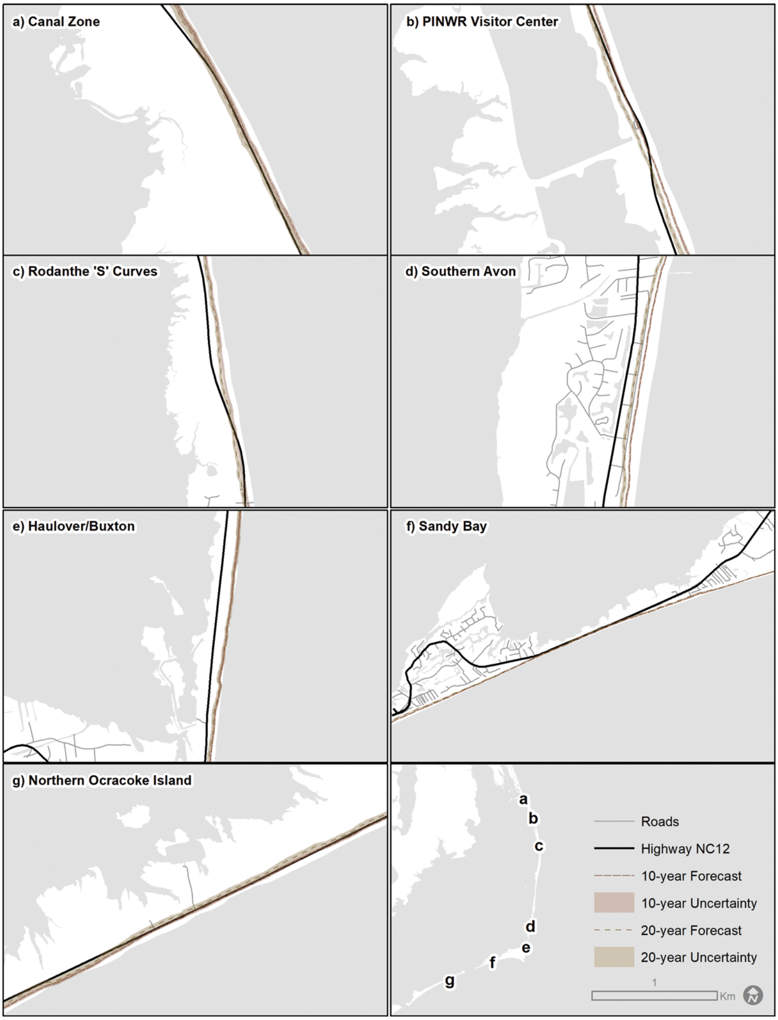

Figure 3. The ten- and twenty-year shoreline position prediction with uncertainty bands based on the linear regression rates calculated from oceanfront shoreline positions along the Cape Hatteras National Seashore between 1998–2022 displayed at each of the seven highway NC 12 hotspots.

level of flood exposure with minimal freeboard (< 0.5 m) and slight (0–0.5 m) to moderate (0.5–1.0 m) inundation modeled for the structures at each light station (Table 3). The results indicate that the depth of inundation increases with an increase in category, as expected. More notably, the results for the Bodie Island Light Station indicate that moderate inundation is generated by a Category 2 hurricane scenario and severe inundation (> 1.0 m) is generated by Category 3 and higher scenarios. The results for the Ocracoke Light Station indicate that Category 4 and higher scenarios are required to

Table 3. Present vulnerability to storm surge for CAHA sites and structures. Data are presented for each feature: First-floor elevation (FFE), and the difference between FFE and SLOSH inundation for each surge category (C1–C5) is given. Positive values indicate no flooding. Negative values indicate slight inundation risk of surge reaching 0–0.5 m above FFE; moderate inundation risk is flooding of 0.5–1.0 m, and severe inundation risk is > 1.0 m of flooding. Features listed by district denoted by two letters in the first column: Bodie Island (BI), Ocracoke Island (OI), LH = Lighthouse; HS = Historic; BD = Non-Historic Building. Ocracoke Island (OI), LH = Lighthouse; HS = Historic; BD = Non-Historic Building.

Structure	FFE (m)	Inundation (m)				
		Category 1	Category 2	Category 3	Category 4	Category 5
	Bodie Island Light Station					
BI HS Bodie Island Lighthouse	1.862	0.249	-0.754	-1.442	-1.884	-2.390
BI HS Bodie Island Oil House	1.862	0.250	-0.753	-1.441	-1.883	-2.388
BI HS Keepers Quarters	1.794	0.186	-0.814	-1.502	-1.942	-2.447
BI HS LH Store House	1.186	-0.423	-1.425	-2.109	-2.547	-3.050
BI BD LH Comfort Station	1.697	0.086	-0.918	-1.597	-2.032	-2.532
	Ocracoke Light Station					
OI HS Ocracoke Lighthouse	1.962	0.667	0.144	-0.185	-0.574	-1.277
OI HS Oil House	1.329	0.033	-0.490	-0.820	-1.207	-1.911
OI HS Keepers Quarters	1.478	0.181	-0.339	-0.671	-1.068	-1.770
OI BD Quarters Generator Shed	1.498	0.203	-0.320	-0.649	-1.040	-1.743
OI HS Tool House	1.197	-0.099	-0.621	-0.952	-1.344	-2.047
OI HS Privy	0.676	-0.621	-1.143	-1.474	-1.864	-2.568

severely inundate most structures at the site. However, these results may be conservative even though the MOMs at high tide were used as the storm surge scenarios because Hurricane Dorian (2019), a Category 1 event when it made landfall in North Carolina, produced severe inundation levels at the site (Avila et al. 2020, NPS 2022b).

Effects of Relative Sea-Level Rise

The results of the future relative sea-level rise exposure assessment indicate that the threshold for tidal flooding or storm surges to inundate roads, recreational areas, habitats, and structures decreases as sea level rises (Figure 4). The findings confirm what might be intuitively surmised, but our results provide valuable, spatially specific information for planning purposes, nonetheless. The highest ground at the Seashore lies around Cape Hatteras and Buxton Woods, which include large, relict dune ridges. Even here, however, the areal coverage of inundation increases with sea-level rise. With increasing sea level, less severe storms are capable of increased flooding, overcoming historical thresholds. Beyond 40–60 cm of sea-level rise, extensive areas of the Seashore could be inundated by Category 1 hurricane surges.

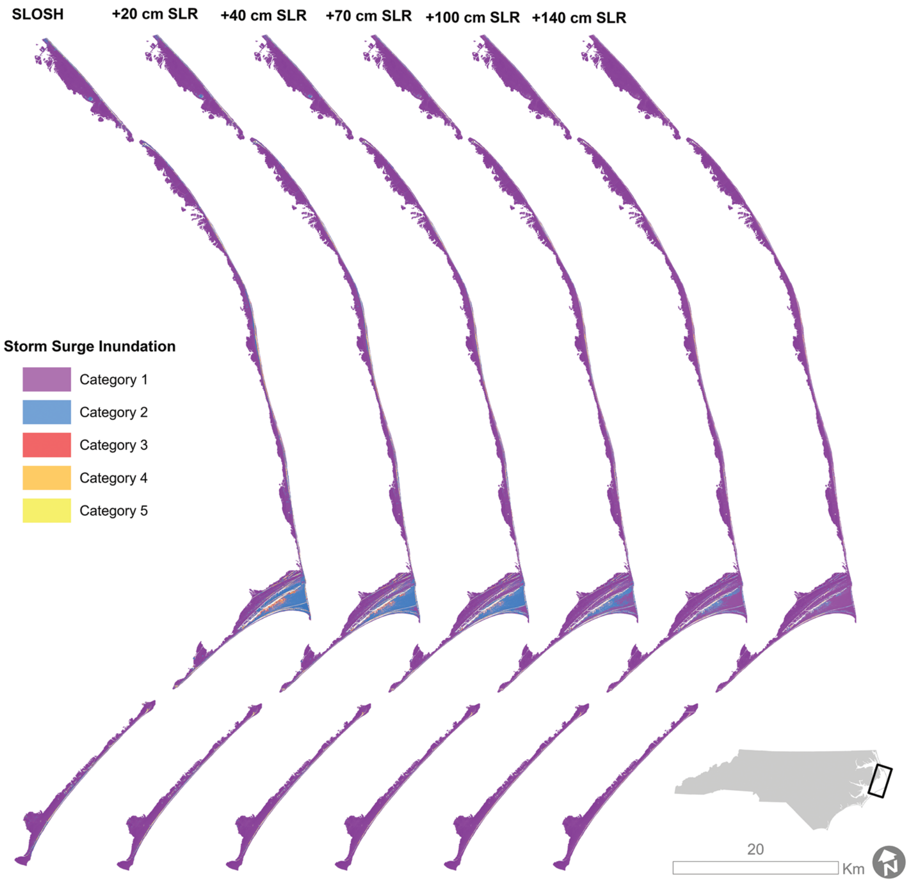

Figure 4. Regional storm surge inundation extent for downscaled SLOSH MOMs under present-day conditions and with various relative SLR scenarios.

DISCUSSION AND IMPLICATIONS

A picture emerges of the evolving implications of sea-level rise to exacerbate the natural process of barrier island transgression, as evidenced by shoreline change and tidal and storm surge flooding. The tendency toward immovable infrastructure, residences, and fixed locations of ecological resources is an imported concept in the dynamic Outer Banks. Centennial- and decadal-scale erosion and retreat are reflected in the geography of the Seashore's transportation system, scores of parcels that lie literally under water, and inexorable erosion and periodic losses of structures to storms each year. The results of the coastal vulnerability analyses can be used to evaluate the viability of the NC 12 transportation corridor for the purpose of: 1) identifying which resilient coastal management strategy (mitigation, adaptation, relocation) should be implemented at erosion hotspots along the Seashore, and 2) prioritizing where future intervention should occur next while recognizing the actions that have been taken historically, recently, and on a recurring basis. Second, results highlight the variable shoreline change rates and inundation patterns that are tightly coupled, wherein reduced beach width and fragmented foredunes are a positive feedback and hazard to the NC 12 corridor unless it is raised or relocated. Indeed, the State of North Carolina, Dare County, and the NPS are supporting projects that reflect this understanding, such as the construction of a causeway over the historic location of New Inlet, and re-routing NC 12 to bypass the highly vulnerable erosion hotspot Rodanthe *S*-Curves.

Of the seven erosion hotspots along the NC 12 transportation corridor on Hatteras and Ocracoke islands, a range of mitigation, adaptation and relocation strategies are being employed (Figure 5). The aforementioned Rodanthe *S*-Curves area (Figure 5A) bypasses the vulnerable section of highway via the new 3.8 km (2.4-mile) bridge completed in July of 2022 that runs from the Pea Island National Wildlife Refuge over the Pamlico Sound and into the village of Rodanthe. This strategy allows for the return to a natural regime of overwash that provides habitat for nesting shorebirds and sea turtles as well as the major benefit of reduced transportation disruption from flooding and potential inlet opening. In contrast, mitigation was the strategy implemented to address the southern Avon (Figure 5B) and Haulover/Buxton (Figure 5C) areas via beach nourishment projects completed in July and August–September of 2022, respectively. While the volume of material added to the dune and beach system affords an increased buffer between the shoreline and highway, renourishment (i.e., replenishment) is recognized as a temporary solution. The initial nourishment project for the Haulover/Buxton area in late 2017/early 2018 provides a reference for the lifespan of beach nourishment projects, yet long-term perennial renourishment looms as a policy concern for both cost, hazard reduction, and sand availability. In another example of mitigation, the north end of Ocracoke Island had installation of some 2,500 large sandbags in 2020–2021 covered with additional volume of dredge material hauled with heavy equipment (Figure 5D). This recent mitigation effort was implemented as a stop-gap measure to protect the highway from becoming undercut by storm surges and recurrent soundside flooding. For the long term, relocation of the South Dock ferry terminal is a strategy that has gained attention. The NCDOT previously conducted an initial feasibility study in 2020, and the NC Ferry Division sought a federally funded feasibility study in 2022 to evaluate the relocation of the South Dock ferry terminal as a long-term solution.

These examples illustrate the developing dynamic of a system of mitigation, adaptation, and relocation. In some cases, mitigation is clearly sought as a short-term solution, either as a transition to a long-term solution or, as in the case of beach replenishment and inlet shoreline stabilization, a decidedly temporary, stop-gap measure to protect transportation infrastructure or buildings. Beach nourishment is the strategy that has been most used along the NC coast to mitigate erosion for the purpose of protecting NC 12 and maintaining the operation of the transportation system. Beach nourishment is an

Figure 5. Photographs of recent coastal adaptation and mitigation actions at the Seashore: A) Rodanthe Bridge (aka the "Jug Handle" bridge) illustrates adaptation by relocation to avoid overwash; B) beach nourishment at Avon and C) Buxton represents short-term mitigation of frequent ocean overwash of NC 12; D) sandbags installed along the northern section of Ocracoke Island are intended as a temporary mitigation response to rapid erosion while various sites are under consideration for the relocation of the South Dock ferry terminal (Photo Credit: Cape Hatteras National Seashore, National Park Service [2021]).

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 and becoming a challenging proposition over decades.

The results and examples described here illustrate a continuum between mitigation, adaptation, and ultimately relocation in the management of NPS assets and resources that considers wider island accessibility, hazards, and community resilience. In addition to these examples, three areas among the identified hotspots remain to be considered for the types of strategies and the prioritization of implementation to improve the viability of the NC 12 transportation corridor and Seashore access. These include the Canal Zone, Pea Island Visitor Center, and Sandy Bay. The Pea Island Visitor Center hotspot is in the most peril based on the current proximity of the shoreline to the highway and results that predict shoreline position based on the linear regression rate calculated from historical shoreline position. Shoreline change rates and forecast positions appear relatively similar for the Canal Zone and Sandy Bay areas. Sandy Bay may be more vulnerable to a breach such as the one that occurred as a result of Hurricane Isabel (2003) due to the narrow width and low subaerial volume of the barrier island at this location. Transportation along the Canal Zone is currently maintained through regular use of heavy equipment to handle the sand that either migrates via aeolian transport or is overwashed during storm events. This strategy is applied to the other two areas as well following storm events. A combination of mitigation, adaptation, and relocation strategies may need to be implemented to address these three areas. Mitigation in the near term through continued use of heavy equipment when necessary as well as the possible nearshore placement of dredge material from adjacent inlets. Adaptation and/or relocation are exemplified by the construction of an elevated highway similar to the Captain Richard Etheridge Bridge that runs over New Inlet within the PINWR and another bridge that bypasses the erosion hotspot entirely in a similar approach to the Rodanthe Bridge.

The storm surge modeling analysis evidences the vulnerability of the structures and infrastructure located on the Seashore to inundation with specific category hurricane events and the evolution of this with sea-level rise. The results indicated that several structures could be inundated beginning with a Category 1 hurricane, and (as expected) the severity of inundation increases with storm severity. The threats posed by sea-level rise include possible increases in flood depth, wave action, and expansion of the extent of inundation even with lesser category hurricanes or storm events. A threshold exists for structures wherein lower-severity storms could see surges reaching the critical elevation of the first floor. Elevating structures, an adaptation strategy, has also been increasingly explored by the NPS. The Keeper's Quarters and other associated buildings at the Bodie Island Light Station, for instance, are being evaluated for elevating the structures to abate the effects of soundside flooding. Elevating the Double Keeper's Quarters at the Ocracoke Light Station is also being pursued, albeit that is the priority of the two as that structure was recently inundated during Hurricane Dorian (2019) (NPS 2022b).

Unlike the Cape Hatteras Light Station, which was relocated over 800 m in 1999 (known as "the move of the century"), the relocation of these other light stations is not something that is actively being considered at this time owing to the fact that storm surge inundation is the primary coastal hazard that currently threatens their structural integrity and accessibility (whereas tidal flooding and shoreline erosion are not imminent threats). In contrast, the Bodie Island maintenance facility and housing complex are assets that are currently being planned for relocation since these facilities are vulnerable to multiple coastal hazards, including coastal erosion and flooding.

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 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 were mapped with baseline sea level. The effect of the addition of sea-level rise is logical and expected, but it is useful to evaluate other areas with low elevations and to visualize for planning purposes. Across much of the Seashore today, a landfalling or nearby passage of Category 2 storm surge is expected to inundate most areas of the Outer Banks, as indicated by modeling with SLOSH and LiDAR DEMs. In the future, even at +20 cm of SLR there is evident expansion of areas vulnerable to flooding by Category 1 and 2 storms. However, this scale of analysis does not allow the assessment of individual buildings. To effect risk reduction for historic resources and overall NPS-managed assets, various adaptation or mitigation options would need to be explored and implemented along the Seashore. The results here illustrate that there is a growing threat from sea-level rise, even if the current climatology of tropical storms were to remain unchanged in magnitude.

A few limitations are notable for this study, necessarily constraining results and recommendations. First, the study made use primarily of existing data, only augmenting these as new imagery and limited field campaigns (e.g., FFE surveys by GNSS) were available. The investigators used the best available coastal elevations. The project was fortuitous with the availability of a recent SLOSH grid for the Hatteras region prepared by the NOAA NWS National Hurricane Center, allowing some improvement to the downscaling of MOM inundation maps as compared to prior studies. Shoreline change analyses were completed for the oceanfront, but calculating estuarine shoreline change rates was not feasible, as only limited shoreline data were available in comparison to oceanfront shorelines and imagery. The vulnerability revealed by static SLR inundation for Ocracoke Island and, to a lesser degree, Bodie Island, is 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 the Seashore, e.g., Haulover or "Canadian Hole," suggests the need to analyze estuarine shorelines for changes affecting park resources.

Several insights and potential benefits of this project may also be synthesized for other NPS purposes. First, beyond historic structures and transportation infrastructure, there are significant potential future impacts of SLR on park natural resources, habitats, and ecology throughout the Seashore. The data acquired for this study could inform modeling efforts related to habitat change and suitability analysis. For example, static SLR and SLOSH grids, LiDAR DEMs, and shoreline data could be assimilated in models such as the Sea Level Affecting Marshes Model (SLAMM) or other marsh response models to evaluate habitat fragmentation, loss, or migration upslope. 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 scenarios is applicable to habitats and even recreational visitor activities (e.g., trails, kitesurfing, windsurfing, fishing, camping or ORV beach use).

CONCLUSIONS

This paper examined the science-based data that are being collected and management efforts underway to inform future planning, intervention, or adaptation to sea-level rise and barrier island evolution. The results help to identify opportunities for mitigation and adaptation as well as potential environmental tipping points and limits to resilience by assessing frequency and magnitude of flooding events and shoreline change. Performing coastal vulnerability analyses can support and enhance coastal management efforts that seek to balance environmental, cultural, and economic benefits. Shoreline change assessment revealed erosional hotspots in relation to the location of historical districts and transportation corridors and highlighted the need for further study of ecological changes.

Several regions within the study area have exhibited long-term oceanfront shoreline erosion. Evaluating the accessibility of the entire Seashore provides a baseline for coastal hazard decision making for historical and cultural resources such as the Bodie Island and Ocracoke light stations as well as other NPS-maintained assets that support natural resource management and visitor use. Accessibility of the Seashore is fundamental to the National Park Service's mission as well as the economic prosperity and cultural heritage of the surrounding communities.

The analysis showed that the linear regression rate (LRR) for shoreline change was a reasonably robust method for analysis even when a limited number of shorelines are available. As the availability of high-resolution LiDAR and satellite, airborne and UAS imagery accrues, this will help to reduce uncertainty in forecasting shoreline position in the future. Nonetheless, the study underscores many factors driving shoreline change including natural (e.g., storm-driven overwash and longshore transport) as well as anthropogenic activities (e.g., beach nourishment, dune stabilization, and sandbags). To understand past and future changes requires including beach nourishment impacts on sediment transport, lagged effects from alongshore pulses of erosion updrift, inlet opening, and other processes that modify the sediment budget (Inman and Dolan 1989). Moreover, the geologic framework and regional-scale morphology may be important for controlling spatial and temporal changes in erosion.

Even though the oceanfront shoreline near most of the Seashore's historic districts exhibits a long-term erosional trend, the present locations of the historic structures still provide adaptive capacity (e.g., relocation or raising freeboard elevation) from sea-level rise. While this study advanced improvements such as first-floor elevation analysis, future studies should consider even more detailed, site-specific assessments that also factor in back-barrier estuarine shoreline movement as well as simulated sea-level rise and changes in storminess 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, lacking morphodynamics and potential non-linear changes which could arise from inlet opening or cumulative impacts of major storms.

Results affirm the widely held concern 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 when updated data become 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.

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