Vulnerability Indicators for Coastal Roadways Based on Barrier Island Morphology and Shoreline Change Predictions

Liliana Velasquez-Montoya, Ph.D., A.M.ASCE; Elizabeth J. Sciaudone, Ph.D., P.E.; Elizabeth Smyre, P.E.; and Margery F. Overton, Ph.D., M.ASCE

Abstract: Coastal roadways are vulnerable to changes in landscape that occur at variable spatiotemporal scales. In particular, highways on barrier islands suffer the consequences of the combined action of the ocean, the back-barrier lagoon, and the morphological changes in the island. Coastal dunes and beaches are typically the only barrier between the ocean and the island’s infrastructure, while low-lying marshes separate the infrastructure from back-barrier lagoons. This work addresses the spatiotemporal variability of these coastal features along a barrier island and proposes a set of vulnerability indicators that allow evaluating past, present, and future vulnerability of a coastal roadway. Systematically collected remotely sensed data were used to digitize dune elevations and oceanfront and estuarine shorelines in the northern barrier island and proposes a set of vulnerability indicators that allow evaluating past, present, and future vulnerability of a coastal roadway. Systematically collected remotely sensed data were used to digitize dune elevations and oceanfront and estuarine shorelines in the northern portion of Hatteras Island, North Carolina, US. Based on these morphological data and their distance to the main roadway on the island, three vulnerability indicators were defined along shore-normal transects: (1) island width <305 m, (2) dune crest elevation <3 m above the highway, and (3) edge of pavement within 70 m of the ocean shoreline. In addition, potentially vulnerable areas of the coastal roadway have been predicted until 2030 based on historical records of shoreline positions (mid-1940s to present). Of the 20 km of roadway analyzed, currently, nearly 6 km meet at least one vulnerability criterion. By year 2030, 9 km of roadway will potentially become vulnerable because of proximity to the shoreline. These results reveal five main regions of concern; of those regions, two breached during Hurricane Irene (2011) and the others have suffered major dune erosion, overwash, and flooding during winter storms and hurricanes. The vulnerability assessment presented here allowed identification of historical, present, and future vulnerable spots along the island and continues to inform the North Carolina Department of Transportation (NCDOT) for their planning and adaption strategies for future phases of highway improvements. The simplicity of the indicators makes them applicable to other coastal roadways and even other types of critical infrastructure in barrier islands and coastal regions. However, if used at different locations, the specific thresholds for the indicators can vary depending on local conditions that may differ from the ones analyzed here. DOI: 10.1061/(ASCE)NH.1527-6996.0000441. © 2021 American Society of Civil Engineers.

Author keywords: Critical infrastructure; Barrier islands; Coastal adaptation; Vulnerability metrics; Pea Island National Wildlife Refuge; Outer banks of North Carolina; Coastal highway.

Introduction

Barrier islands constitute 10% of the world’s coastlines (Stutz and Pilkey 2011). The main processes known to control barrier island dynamics are tidal range and wave climate (Hayes 1979). Other controlling variables shaping their morphology include relative sea level change, storms, geology, sediment supply, wind, and currents (Cooper et al. 2012; Curry 1964; Hayes and FitzGerald 2013; Houser et al. 2008; Mulhern et al. 2017). Barrier island stability is modulated by biophysical feedbacks between dune erosional and recovery processes (Durin Vincent and Moore 2015). Barrier islands tend to migrate upward and landward in response to relative sea level rise (Bruun 1962). Landward migration is driven by the sediment transport that occurs during storms when the total water level exceeds the dune crest creating washover fans landward of the dune (Donnelly et al. 2006). In addition, barrier islands migrate in the along-shore and cross-shore directions via inlet dynamics (Doughty et al. 2006; Leatherman 1979; Rosati et al. 2010; Nienhuis and Lorenzo-Trueba 2019; Armon and McCann 1979; Leatherman 1983). These natural processes move sediments from the beach to the back barrier and across the nearshore, causing barrier islands to be dynamic coastal landforms. Despite—or in some cases, because of—this dynamism, barrier islands are some of the preferred locations for living and vacationing in the US (Crossett et al. 2013; Zhang and Leatherman 2011). This situation has resulted in the development of their land and subsequent need for critical infrastructure. Consequently, the evolving nature of barrier islands and their tendency to be narrow and low-lying continuously poses challenges to the management of this infrastructure.

Studies by Dolan and Walker (2006), Douglass et al. (2014), Ensard et al. (2001), Hansen and Sallenger (2007), and Judge et al. (2003) have identified the main coastal processes that increase the...
vulnerability of infrastructure and coastal communities on barrier islands. Those processes are storm surge, sea level rise, extreme waves, excess runoff in lagoons, shoreline and dune erosion, overwash, and island breaching, and they occur at temporal scales ranging from hours and days up to a few decades and centuries. Infrastructure exposure to flooding, water velocities, sand deposition, and wave action resulting from the aforementioned phenomena is the main cause of structural damage to the built environment in coastal regions (Esnard et al. 2001; Smalegian and Irish 2017; Tomiczek et al. 2017) and specifically to coastal highways and bridges (Anarde et al. 2018; Douglass et al. 2014; Padgett et al. 2008). Coastal roadways built at grade level can suffer from severe structural damage such as erosion or scour of the embankments over which they are built, pavement undermining, fracture, and deterioration (Douglass and Krolak 2008). Other moderate issues that can result in transportation corridor downtime and increasing driving hazards include sand and debris deposition over the roadway and standing water.

Coastal roadways constitute the first line of public infrastructure landward of the ocean and estuarine shorelines. Given the limited number of major roadways in barrier islands, they are considered critical infrastructure as they provide routes of access and mobility for local residents and tourists. Moreover, they are the main route of evacuation during storms and the main terrestrial infrastructure to mobilize emergency responders (US Department of Homeland Security 2019). Thus, to ensure the longevity and proper service of this critical infrastructure, the design of coastal roadways, their maintenance, and their operability require strategic planning to account for present and future morphological and environmental conditions of barrier islands (Transportation Research Board and National Research Council 2008).

Historically, vulnerability studies have provided transportation authorities with the information required for management decisions (Douglass and Krolak 2008). Typical environmental variables used as vulnerability criteria for coastal regions include mean and maximum beach elevation, horizontal shoreline displacement (erosion/accretion), geomorphology, sea level rise trends, and expected mean and extreme water levels and waves (Gornitz et al. 1994). More recently, the US Federal Highway Administration (FHWA) has published guidelines for the assessment of highway vulnerability under varying climate change scenarios (Filosa et al. 2017). However, there are still very few vulnerability assessments of roadways to coastal hazards in the literature, and it is rare that transportation authorities establish long-term monitoring efforts to collect systematic data that allow assessment of road vulnerabilities through time. This issue may be overlooked for inland infrastructure, but gains importance in dynamic regions such as barrier islands, in which morphological conditions are continuously evolving.

To address this issue, this study aims to propose a framework to describe the spatiotemporal vulnerability of roadways to coastal processes using three morphological indicators based on the dune height relative to the roadway, barrier island width, and distance of the roadway to the ocean shoreline. A case study and a long-term monitoring program are detailed to provide an example of strategic planning for a coastal roadway. Specifically, this study presents a compilation of the vulnerability analyses on the northern portion of Hatteras Island, North Carolina, US, and the North Carolina Highway 12 (NC 12) in the last 8 years (2010–2018) of a Coastal Monitoring Program (CMP). The last section discusses the steps that the North Carolina Department of Transportation (NCDOT) has taken for strategic planning for the NC 12 and the applicability of this approach to other regions with coastal roadways and critical infrastructure.

### Study Area

#### Pea Island

The study area is located on Hatteras Island on the East Coast of the United States. Hatteras Island is part of a barrier island system known as the Outer Banks of North Carolina, with the northern part of the island commonly known as Pea Island because this portion was once separated from Hatteras Island by an inlet. It is home to the Cape Hatteras National Seashore, which is managed by the National Park Service and the Pea Island National Wildlife Refuge, which is managed by the US Fish and Wildlife Service. The area of interest is a 20-km (12.5 mi) long portion of Hatteras Island extending from the north tip of the island to the community of Rodanthe (Fig. 1) with widths ranging from 200 m (656 ft) to 1,700 m (5,577 ft).

The island, bordered by Oregon Inlet in the north, the Atlantic Ocean on the east, and the Pamlico Sound on the west, has a ridge of dunes with maximum elevations varying between 3 and 10 m (NAVD 88) (Sciaudone et al. 2016). These dunes date back to the 1930s when the Civilian Conservation Corps (CCC) built them as part of an erosion control project known as the Dune Stabilization Project (Birkemeier et al. 1984). In the northern half of the refuge, the dunes are unvegetated and unconsolidated piles of sand that are continuously rebuilt via bulldozing within the easement of the highway that runs along the island. Historical records indicate that these northern exposed dunes with little to no vegetation can easily lose between 1 and 2 m in elevation in any given year due to Aeolian processes and nor’easters (Sciaudone et al. 2016). In the southern half of the refuge there is a section in which dunes are vegetated and erosional changes have been occurring since 2016, mostly on the dune face. At the southernmost end of the refuge, the island narrows, and dunes are similar to those unvegetated and unconsolidated piles of sand seen in the north. Dune growth on Pea Island is mainly driven by anthropogenic processes (rebuilding), and there is no evidence of recent natural dune growth along the refuge.

Since 1938, this section of the island hosts the Pea Island National Wildlife Refuge (PINWR), which was established to provide habitat and protection for endangered species, nesting, resting, and wintering habitat for migratory birds, and to provide opportunities for public enjoyment of wildlife and wildlands resources (US Fish and Wildlife Service 2016). The infrastructure on the refuge is relatively sparse; consisting of a visitor center, a few facilities for the refuge operations, three man-made impoundments built in the late 1940s and 1960s to enhance habitat quality for migratory waterfowl, and the NC 12 coastal highway, which is a coastal highway. The latter went from a sand trail to a paved road in the 1950s. Related to the NC 12 transportation corridor are the Herbert C. Bonner Bridge over Oregon Inlet and a terminal groin built on the north tip of the island (Fig. 1) to protect the southern abutment of the bridge from scour due to inlet migration. The Bonner Bridge reached its design life and was recently replaced by the Marc Basnight Bridge, which runs almost parallel to the older bridge alignment.

In this region the tides are semi-diurnal with a range of 1 m in the ocean side and 30 cm in the sound side (Inman and Dolan 1989). The mean sea level at the closest tidal gauge (NOAA Station Oregon Inlet Marina, ID: 8652587) is 0.038 m relative to NAVD 88. The region has a seasonal wave climate, during the summer calm conditions prevail, but occasional hurricanes and tropical storms can reach the area. Winter on the other hand, is dominated by frequent nor’easters. These extratropical storms bring strong winds and waves from the northeast that have enough energy to drive major morphological changes in the study area, mostly related to dune erosion and overwash (Inman and Dolan 1989). Fig. 2 shows the timeline of storms, including named hurricanes and
nor'easters, that occurred from 2010 to 2018. The ocean-side data, recorded at a station 50 km north of Pea Island, indicate that hurricanes and major storms can generate significant wave heights higher than 4 m at 17 m depth, while both ocean- and sound-side maximum water levels can reach values above 1 m (NAVD 88).

Hurricanes Irene and Sandy have been the most intense storms that impacted the study area between 2010 and 2018; however, they were very different events. Hurricane Irene traveled north through the Pamlico Sound in August 2011 generating a sound-side surge of 1.9 m (Kurum et al. 2012), maximum water levels up to 2.1 m (NAVD 88), and opening two breaches along Hatteras Island (Clinch et al. 2012; Hardin et al. 2012). The breaches occurred at narrow locations in the island in which remnants of paleo-inlets (e.g., ponds and estuarine channels) were hydraulically connected to the sound. The paleo-inlets that have existed at those locations are known as New Inlet and Chickinacommock Inlet (Birkemeier et al. 1984; Fisher 1962; Mallinson et al. 2010).

The smaller of the breaches opened in the south end of the PINWR (Rodanthe Breach) and closed within days assisted by earth-moving efforts within the NC 12 easement. The other breach opened in the middle of PINWR (Pea Island Breach, north portion of the New Inlet region in Fig. 1(b), it remained open for less than two years and closed naturally after a stormy winter in May 2013 (Safak et al. 2016; Velasquez-Montoya et al. 2018). Although both breaches destroyed portions of NC 12, the transportation corridor was restored via road reconstruction at the southern breach and construction of a temporary bridge at the site in the center of the PINWR.

Hurricane Sandy, on the other hand, stayed offshore of the Outer Banks, causing ocean shoreline erosion and dune overwash from the ocean side [Fig. 1(a)] degrading portions of the dune field along PINWR (Overton 2012). Other significant storms during the 2010–2018 period include Hurricanes Joaquin (2015), Hermine, and Matthew (2016) and winter storm Riley (2018).

**NC 12 Highway**

The NC 12 highway is a state highway that runs from Corolla to Cedar Island in North Carolina. In this study, only 20 km of road along the PINWR are considered. NC 12 is a two-lane road with 3.35-m (11-ft) wide lanes plus 1.22-m (4-ft) wide shoulders. It carries local and regional traffic providing the only roadway access and...
evacuation route for Hatteras Island and the communities located south of the PINWR. Based on data from 2002, the average annual traffic volume of NC 12 in the study area is 5,400 vehicles per day and 8,800 vehicles per day during the summer tourist season (FHWA 2008). These numbers and tourist interviews by Seekamp et al. (2019) suggest that the access to the Outer Banks via the NC highway 12 is one of the main drivers of tourism in the region.

Long-term coastal processes, inlet dynamics, and storm events drive the morphology of Pea Island and, in turn, the vulnerability of the road. The proximity of the NC 12 to the shoreline has made sections of this road vulnerable to flooding, sand deposition over the pavement, and pavement fracture and undermining [Figs. 1(a–c)]. Tropical cyclones tend to cause the most severe structural damage in the roadway, and they may hit the region multiple times per year. Nor’easters are constant during the winter and typically cause dune erosion and overwash in regions of degraded dunes; they can result in road closures, but not necessarily structural damage. Since state regulations do not permit erosion control structures along the ocean shoreline, the only protection of the roadway from the action of the ocean are the beach and dune ridge along Pea Island. Nonetheless, long-term erosion and storms have eroded portions of these dunes (Overton and Fisher 2004; Sciaudone et al. 2016), which are constantly maintained and rebuilt within the highway right-of-way by NCDOT. This spatial restriction results in dune rebuilding focusing on tall instead of wide dunes.

The Final Environmental Impact Statement for the replacement of the Bonner Bridge (NCDOT 2008) reported the types of maintenance activities and the general frequency with which they are necessitated in different areas along the refuge. In general, road scraping is required one to two times per month, dune maintenance two to three times per year, dune rebuilding one to two times per year, and dune translation one to two times per year. Given the aforementioned circumstances, the history of damage and repairs for NC 12 includes frequent clean up and dune reconstruction operations, road relocations, and implementation of soft mitigation alternatives to protect the roadway. Table 1 summarizes the main state and federal actions taken in the PINWR section of the highway.

In the timeframe of this study, the maintenance expenses related to coastal processes affecting the road have remained above $300,000/year. In fact, between 2010 and 2017, NCDOT spent nearly $27.2 million in disaster and hurricane recovery, special projects, and maintenance of NC 12 within the study area. In addition, a federally funded beach nourishment project placed nearly 1.6 × 10^6 m^3 of sand near the southern edge of the PINWR for protection of the NC 12 highway in 2014 [Fig. 1(c)] (Overton 2015). According to the National Beach Nourishment Database (Campbell and Benedet 2006), the cost of the latter project was $19.4 million.

**Background Information on the Coastal Monitoring Program (CMP)**

Oregon Inlet, located on the north end of Pea Island (Fig. 1), was a naturally migrating inlet moving south at an average rate of 22.9 m/year (75 ft/year) and west at an average rate of 4.9 m/year (16 ft/year) (Inman and Dolan 1989). In 1961, the Herbert C. Bonner Bridge was constructed over Oregon Inlet to extend NC 12 to the south, providing vehicle access to Pea Island and Hatteras Island. The bridge design took into account estimates of future inlet migration relative to the design life of the bridge. However, in the 1980s, inlet migration increased, and the southern end of the bridge was threatened. Inman and Dolan (1989) attributed the acceleration of inlet migration in part to dredging of the inlet and disposal of material offshore.

In 1988, NCDOT assembled a task force to assess the risks to the bridge associated with inlet migration and to evaluate several protection alternatives. A terminal groin on the north end of the PINWR was recommended to stabilize the south side of the inlet and protect the bridge abutment. Because the groin was to be built on land managed by the US Fish and Wildlife Service and within the Cape Hatteras National Seashore, NCDOT was required to ensure that the groin would not accelerate the erosion of the downdrift shoreline. This requirement led to the beginning of the terminal groin monitoring program to assess shoreline changes over a 10-km stretch of the island located south of Oregon Inlet (Overton et al. 1992).

Construction of the terminal groin began in the fall of 1989 and was completed in 1991. Since then, the monitoring program has been in place to assess shoreline response to the structure along Pea Island. The terminal groin monitoring program analyzed aerial photographs taken every two months as well as immediately after...
Table 1. Summary of the major highway protection/reconstruction actions along the portion of NC 12 within the PINWR

<table>
<thead>
<tr>
<th>Year</th>
<th>Action</th>
<th>Location</th>
<th>Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 1967</td>
<td>Road relocation</td>
<td>Canal Zone, 3.7 km south of the Bonner Bridge</td>
<td>Frequent overwash</td>
</tr>
<tr>
<td>December 1988</td>
<td>Road relocation</td>
<td>S-Curves</td>
<td>Long-term shoreline erosion and overwash</td>
</tr>
<tr>
<td>1989–1991</td>
<td>Construction of terminal groin. This structure was allowed as an exception to existing rules that prohibit permanent structures in the ocean shoreline.</td>
<td>S-Curves</td>
<td>Southward migration of Oregon Inlet and potential encroachment of the inlet into the southern abutment of the Bonner Bridge</td>
</tr>
<tr>
<td>1992</td>
<td>Sandbags placement</td>
<td>Old Sandbag Area</td>
<td>Overwash and flooding</td>
</tr>
<tr>
<td>1996</td>
<td>Road relocation, sandbags removal and dune reconstruction</td>
<td>Old Sandbag Area</td>
<td>Sandbags were temporary solution to overwash and flooding</td>
</tr>
<tr>
<td>2007–2008</td>
<td>Dune reinforcement with sandbags</td>
<td>S-Curves, just north of the community of Rodanthe</td>
<td>Long-term erosion and flooding</td>
</tr>
<tr>
<td>2011</td>
<td>Temporary bridge</td>
<td>New Inlet</td>
<td>Barrier island breaching</td>
</tr>
<tr>
<td>2011</td>
<td>Road and dune reconstruction</td>
<td>S-Curves</td>
<td>Barrier island breaching</td>
</tr>
<tr>
<td>2014</td>
<td>Beach nourishment and dune reconstruction</td>
<td>S-Curves in narrow section of Pea Island</td>
<td>Ocean shoreline erosion due to Hurricane Sandy and subsequent nor’easters</td>
</tr>
<tr>
<td>2016–2018</td>
<td>Pea Island interim bridge</td>
<td>New Inlet</td>
<td>Barrier island breaching (replacement for temporary metal bridge built in 2011)</td>
</tr>
<tr>
<td>2018–2020</td>
<td>Rodanthe jug handle bridge</td>
<td>S-Curves</td>
<td>Long-term erosion and frequent impacts</td>
</tr>
</tbody>
</table>

Sources: Data from Cole (1989); Overton and Fisher (2004); Sciaudone et al. (2016); Stone et al. (1991).
Note: This list does not include maintenance or repair work associated with the Herbert C. Bonner Bridge or sand disposal from dredging Oregon Inlet.

severe storms. The photographs were used to digitize the shoreline and to determine if the terminal groin was causing accelerated shoreline erosion downdrift of Oregon Inlet via comparison with the shoreline position predicted from historical rates. To date, the data indicate that the terminal groin has not caused adverse impact in the downdrift ocean shoreline (Joyner et al. 1998; NCDENR 2010; Overton et al. 1992; Overton and Sciaudone 2018).

In 1990, NCDOT began studying alternatives to replace the Bonner Bridge before reaching its design life cycle, with the preferred alternative selected in 2010 (NCDOT 2017). The 2010 Record of Decision set forth a long-term plan for NC 12 between Oregon Inlet and the community of Rodanthe that included a parallel bridge corridor across Oregon Inlet and a phased approach to maintaining the transportation corridor along Pea Island as part of the NC 12 Transportation Management Plan. A component of this plan is the current CMP, which is designed to provide the data needed for engineers to assess the vulnerability of the highway along the PINWR and to assist the agencies in deciding when and where the planning efforts for future phases of NC 12 should begin. The CMP study area extends approximately 21 km (13 mi) south of Oregon Inlet to Rodanthe, including the entire width of Hatteras Island between the ocean and estuarine shorelines. Currently, the CMP includes the bimonthly collection of aerial photographs and digital terrain models four times a year.

The CMP provides an example of a long-term monitoring effort to collect systematic data that allow assessment of road vulnerabilities through time. The current expanded program includes a prognostic component to identify vulnerable areas of the coastal highway at the 2030 planning horizon (Overton and Sciaudone 2018). A critical aspect of the CMP is that it is not a static program; instead, its scope evolves over time as additional information becomes available year by year and NCDOT’s management challenges change along the transportation corridor.

Data and Methods

Data for this study consisted of aerial photographs of the barrier island with resolution varying from 0.15 m (0.5 ft) to 0.3 m (1 ft) from mid-2011 to 2018, provided by NCDOT on a bimonthly basis (generally in February, April, June, August, October, and December, although weather conditions occasionally necessitate changes in the flight timeline). NCDOT also provided photogrammetrically derived digital terrain models with elevation in NAVD 88 four times a year (generally February, April, August, and October). The aerial imagery and the elevation data cover the whole subaerial extent of the PINWR, from the terminal groin in the north, to the limit of the community of Rodanthe in the south. These data were imported into ArcGIS, where, by means of digitization, key morphological features of the barrier island and the road were computed. Key features included the ocean shoreline, estuarine shoreline, dune crest location and elevation, road elevation, distance from the eastern edge of pavement to the ocean shoreline, and island width (Fig. 3).

The shoreline is represented as the visible wet-dry line for sandy beaches on the ocean side, and the limit of the marsh vegetation is used to represent the estuarine shoreline. In the regions in which the estuarine shoreline is sandy, the wet-dry line is used. It is noted that when channels or ponds wider than approximately 10 m are hydraulically connected to the sound, the estuarine shoreline includes the outline of those channels. The wet-dry line (also known as the high-water line) is used because it has a smaller horizontal displacement than the swash terminus, therefore it is more suitable for long-term shoreline change analysis (Dolan et al. 1980). Since the beginning of the CMP in August 2010, 44 ocean shorelines have been mapped. Additional shorelines were digitized from historical imagery available along the PINWR (e.g., t-sheets and aerial images from state and federal agencies that date back to the 1940s). The number of shorelines available along Pea Island and their range of dates are shown in Fig. 4. It should be noted that the terminal groin has been shown to be influencing the behavior of the first 5 km of shoreline (Overton et al. 2004), therefore only shorelines after initiation of groin construction in 1989 are considered for analysis in the northern part of the island.

The dune crest elevation, the distance from the edge of pavement to the ocean shoreline, and the island width are computed at predefined shore normal transects with 45.7-m (150-ft) spacing...
These transects extend across the whole barrier island from a fixed baseline offshore. The dune crest is computed as the maximum elevation between the eastern edge of the pavement of NC 12 and the ocean shoreline. This computation is based on interpolated profiles along the transects using elevations from the digital terrain models. Fig. 3 shows a schematic of these three morphological variables.

**Vulnerability Indicators**

To assess the overall vulnerability of the road at each transect, researchers and NCDOT personnel have worked together to define specific vulnerability criteria for NC 12. The criteria have been revised over time; here we only present the most recent three criteria that are evaluated at the end of each calendar year, as shown on Fig. 5. These three vulnerability criteria are based on historical records of road damage related to morphological changes in Pea Island. It should be noted that despite the fact that the specific thresholds for each indicator are specific to Pea Island and NC 12, the overall definition of the indicators is relevant to other barrier islands, as most of these coastal environments are narrow, low-lying, and are prone to overwash and breaching from either side of the island during coastal storms.

**Island Width Less Than 305 m (1,000 ft)**

The island width is measured as the horizontal distance from the ocean shoreline to the estuarine shoreline. When this distance is less than 305 m (1,000 ft) the road is considered vulnerable to flooding from both the ocean and the sound side. It should be noted that if a robust dune system exists on one side of the road, this criterion still allows accounting for vulnerability to flooding from the body of water on the other side of the island. This consideration is of particular importance for barrier islands located in front of large lagoon systems, such as the Outer Banks, in which storm surge rebounds from the sound side contributes to flooding and island breaching as hurricanes move north (Bush et al. 1996; Clinch et al. 2012; Kurum et al. 2012).

Initially, the portions of the road located within the 10% narrowest sections of the island (≈335 m) were identified as vulnerable to flooding from both sides. This threshold was subsequently modified to the 305-m threshold based on the island widths at the locations along the Outer Banks in which two breaches opened.

---

Fig. 3. (Color) Schematic of (a) island width; (b) distance from edge of pavement to ocean shoreline; and (c) dune crest elevation computed at transects. [Aerial images (a and b) courtesy of NCDOT.]

Fig. 4. (Color) Spatiotemporal distribution of number of shorelines available to compute change rates (erosion/accretion) along PINWR. (Aerial images courtesy of NCDOT.)
during Hurricane Irene in August 2011 (described in the “Study Area, Pea Island” section) and one breach opened during Hurricane Isabel in 2003. The latter, located 45 km south of the southern end of the PINWR, between the villages of Hatteras and Frisco (Wamsley and Hathaway 2004). The island width as measured from channels and ponds hydraulically connected to the sound at the aforementioned locations where the island breached was <305 m. This distance becomes a critical indicator of island breaching and back-barrier flooding when there are estuarine channels or bodies of water that funnel storm surge toward a narrow section of the barrier island (e.g., tidal creeks, remnant channels from historic river channels created during periods of lower sea level, or paleo-inlets). The presence of those channels has historically coincided with island breaching locations in the Outer Banks. Therefore, recognizing the importance of the sound-side morphology and hydraulic connectivity, this criterion considers vulnerability to island breaching and flooding from both the ocean and the sound.

It is important to realize that vulnerability to island breaching does not only depend on sound-side morphology and island width; other variables of critical importance include island maximum elevation and volume of protective sand from the roadway to the shoreline (dune and beach). To account for those variables, two additional vulnerability indicators have been developed.

Dune Crest Elevation Less Than 3 m (10 ft) above NC 12

The vertical distance between the dune crest and the highway is measured at each transect, if that distance is less than 3 m, that section of the roadway is considered vulnerable to flooding and sand deposition from dune overwash. This criterion was defined based on Storm-induced BEAch Change Model-SBEACH (Larson and Kraus 1989) simulations used to determine the likelihood of occurrence of dune overwash due to total water level probability for the region. Overton and Fisher (2007) found that a dune template with a dune crest located 3 m above the roadway, such as the one shown in Fig. 6, has a 50% chance (+/−5%) that about 45% of the dune would be eroded due to a single storm in a 4-year period.

According to the storm impact scale proposed by Sallenger (2000), the elevation of the total water level relative to the dune toe and dune crest can result in four storm impact regimes (1) swash: no net change in the dune, (2) collision: net dune face erosion, (3) overwash: dune is overtopped and eroded sediments are transported landward of the dune crest, and (4) inundation: dune completely eroded. In the context of roadway vulnerability, dunes should be high enough to remain in the first two regimes that would prevent immediate road damage.

Considering that the average elevation of the road is 1.3 m (NAVD 88) and the results from Overton and Fisher (2007) on the dune dimensions mentioned at the beginning of this section, in order for the road to not be vulnerable to overwash, the dune crest must be higher than 4.3 m (NAVD 88). This dune crest elevation would be under the collision regime for a typical winter storm in the Outer Banks, which as defined by Sallenger (2000), has a deep-water wave height of 2.5 m, a period of 7 s, and a water level due to surge and tide of 1.2 m.

The 3-m relative elevation threshold was defined for unvegetated dunes. Given that unvegetated dunes erode more easily than vegetated ones (Durán Vinent and Moore 2015; Feagin et al. 2015; Silva et al. 2016), it is assumed that the threshold accounts for the worst case scenario and it is also applied to vegetated dunes.

Critical Buffer

The road is potentially vulnerable to ocean-side flooding in areas in which the eastern edge of pavement is within 70 m (230 ft) of the present ocean shoreline. This criterion was first defined for NC 12 by Stone et al. (1991) as the 230 ft critical buffer; it is based on the work of Cole (1989), who identified problem areas along the transportation corridor and typical distances at which NCDOT initiated previous remedial actions, including road relocation or nourishment projects. Those analyses indicate that most remedial actions were taken when the eastern edge of pavement was at an average distance from the shoreline of 66 m. The 70-m threshold is more conservative and provides the distance required to sustain the minimum configuration of a beach and a barrier dune such as the one shown in Fig. 6. This distance allows for a 30-m (100-ft) wide

© ASCE 04021003-7 Nat. Hazards Rev.
beach with a dune having a 1:5 seaward slope; 1:3 landward slope, and a dune crest 4.5-m (15-ft) wide and 4.5 m above the road (just above the dune crest elevation criterion). This profile approaches the recommended beach design templates developed by the US Army Corps of Engineers based on SBEACH simulations and economic optimizations (USACE 2002). Besides, at 70 m (230 ft) from the shoreline, dunes become vulnerable to storms with return periods as low as 3–5 years (Overton and Fisher 2004). This criterion, in combination with indicator 2, is considered as proxies for protective beach and dune volume, and both of them allow accounting for the vulnerability of the road to ocean-side processes such as flooding, long-term and short-term erosion.

**Vulnerability Composite**

This study compiled and mapped 8 years of data along the barrier island to compare the vulnerability of the highway, year by year, and analyze the evolution of each indicator through time and space. A composite of all indicators was built for each year by adding each indicator as a single factor (indicator 1 + indicator 2 + indicator 3), resulting in values from zero to three, in which zero means no vulnerability and three is the highest possible vulnerability when the three vulnerability criteria are met and the roadway is under imminent risk of damage.

It should be noted that each indicator addresses vulnerability of the road to different processes, therefore even at locations with a vulnerability composite with a value of 1 or 2, it is likely that the transportation corridor will experience moderate and severe damage, respectively. However, the severity of road damage depends on the criteria met. Therefore, the composite should be analyzed in combination with the individual criteria. For example, if the dune elevation is low relative to the road (indicator 2) and this is the only criteria met for a set of transects, dunes could be overtopped during a storm, leading to sand being deposited over the pavement. Road damage will be even more likely and severe if, in addition to meeting the aforementioned criterion, the road is within 70 m of the shoreline (indicator 3). If these two criteria are met, sand deposition over the road, flooding, and road undercutting become possible. If on top of that, the island is narrow (indicator 1), road damage will be imminent during a major storm. Under this circumstance, in addition to the damages previously listed, flow could develop from ocean to sound or vice versa, potentially leading to an island breach and complete removal of the roadway.

**Prediction of Highway Vulnerability**

In addition to the previously described vulnerability criteria, areas in which the shoreline would be expected to recede to the critical buffer zone and decrease the island width to the vulnerability criterion are predicted in 2-year increments until 2030. Generally speaking, the identification process consists of predicting the expected position of the ocean shoreline every two years until 2030 and comparing it with the 70-m critical buffer and the island width criterion as defined in the previous section. These computations are completed for each transect along the PINWR.

The first step in this process is to compute the ocean shoreline change rate based on shoreline positions relative to an offshore baseline. The linear regression method is used to compute the shoreline change rate based on historical shoreline positions including data that go back to the 1940s as well as that collected since the beginning of the terminal groin monitoring program and the CMP (shown in Fig. 4). The linear regression method has been proven to be a reliable predictor for shoreline trends for long-term intervals (Crowell et al. 1997; Douglas et al. 1998; Luijendijk et al. 2018; Montaño et al. 2020; Overton et al. 2004). In addition, this method minimizes the bias toward underpredicting or overpredicting erosion based on the current position. Nevertheless, shoreline change trend may not always be a simple linear relationship, and uncertainty exists in any shoreline prediction.

To account for uncertainty, this study employed prediction intervals to provide an estimate of the range of potential shoreline positions at each transect into the future. A prediction interval is an estimate of a range in which future observations will fall, with a certain probability, given what has already been observed (i.e., a 95% prediction interval indicates that there is a 95% probability that a future observation will be contained within the prediction interval).

In this study, a 95% symmetric prediction interval was used. Given the differences in shoreline behavior along the island and the number of shoreline positions at each transect and their temporal availability, the width of the prediction interval is variable between transects (“Results” section presents the details). It is assumed that the uncertainty captured in the prediction intervals allows accounting for the shoreline response to local sea level rise by the year 2030. This assumption is based on the relative sea level rise rate of 4.69 mm/year reported at the closest NOAA tidal gauge (Station 865287 Oregon Inlet Marina) and a beach in equilibrium with the typical morphology of the study area (i.e., grain size = 0.3 mm, depth of closure = 8 m, and a berm height = 2 m). Using the Brunn Rule (Bruun 1962), the expected shoreline erosion rate due to sea level rise is 0.24 m/year, which translates into nearly 2.64 m of shoreline erosion by 2030. As shown in the results, 2.64 m of shoreline erosion is far less than the uncertainty attributed to predicting the shoreline position in any year.

Once the shoreline change rates and their corresponding prediction intervals are computed for each transect, the second step consists of predicting the shoreline position by using the linear regression trend at each transect and comparing the predicted shoreline position with the 70-m critical buffer. The landward-most shoreline position in the 95% prediction interval range is considered a proxy for the potential high-erosion shoreline position, while the seawardmost position provides an estimate of the low-erosion case. This band of expected positions is compared with the 70-m critical buffer to assess the potential future vulnerability of NC 12 at each transect. Using a conservative approach, any location in which the high-erosion shoreline position recedes to or beyond the 70-m critical buffer is identified as potentially vulnerable in the future. Similarly, the island width is measured between the estuarine shoreline and the high-erosion ocean shoreline, areas in which this distance is less than 305 m are considered potentially vulnerable in the future. Changes in estuarine shoreline position are at least one order of magnitude smaller than ocean shoreline changes, therefore it is assumed that the potential changes in estuarine shoreline are within the uncertainty range accounted for by use of the high erosion line.

A composite of potential vulnerability is created based on the two criteria mentioned previously. The dune elevation criteria is not included in the assessment of future vulnerability as it is uneconomical to accurately predict dune elevation in a decadal time scale, especially when storm frequency and anthropogenic changes to the environment are uncertain. Therefore, predicting future dune elevations are beyond the scope of this paper.

**Results**

The identification of the spatiotemporal variability of the vulnerability indicators along NC 12 was completed using 9 years of compiled data from 2010 to 2018, as shown in Fig. 7. This figure shows where and when each indicator (1, 2, and 3) was met or not. The vulnerability indicators were neglected at the six transects that intersect the interim bridge built over Pea Island Breach because the bridge is an elevated structure and it was built to withstand a breach.
similar to the one that opened in 2011. To facilitate description of the results, the study area was subdivided into zones named after island and road characteristics [Fig. 7(a)].

**Individual Vulnerability Criteria**

There are four sections in the southern half of the island that have reached the threshold of island width (indicator 1) and remained narrower than 305 m from 2010 to 2018. Of those four sections, two already breached during Hurricane Irene in 2011 (horizontal bar with diagonal lines in Fig. 7). The other two correspond to the location of the historical New Inlet (star in Fig. 7) and to the narrowest section along the S-Curves (so named because of the road’s curvature) in which the beach nourishment took place in 2014 [Fig. 1(c)]. The other few spots in which island width has been less than 305 m have occurred intermittently due to hydraulic connectivity of the sound with the salt flats and estuarine ponds that could potentially drive flow through the island.

The dune crest vulnerability criterion (indicator 2) occurs more often in space and time than the other two criteria (Fig. 7). It is

---

**Fig. 7.** (Color) Spatiotemporal vulnerability indicators and composite along Pea Island (2010–2018). Three center panels (b, c, and d): black and white areas indicate when and where each criterion was met (YES) or not met (NO). Panel (e) shows composite of vulnerability criteria (indicator 1 + indicator 2 + indicator 3). Green colors indicate transects and years for which none of criteria were met, yellow indicates that only one criterion (any of three) was met, orange indicates two criteria were met, and red indicates that three criteria were met at a particular location and year. On panel (a), star corresponds to location of historical New Inlet. Horizontal bar with diagonal lines on panels (b), (c), (d), and (e) indicate regions in which Pea Island breached during Hurricane Irene in 2011. (Aerial images courtesy of NCDOT.)
especially recurrent in a 5 km section along the Canal Zone and North Pond, in which the dunes are unvegetated and continuously eroded by winds and waves. It should be noted that this indicator became prevalent in 2012, the year in which Hurricane Sandy heavily eroded the dunes of Pea Island. In some sections, this criterion was met early, but the trend was then reversed when NCDOT conducted dune replenishment for highway protection. Unsurprisingly, the two other sections in which the dune crests have been less than 3 m over the road are located around the regions that were breached during Hurricane Irene.

The road has been within a 70-m buffer from the ocean shoreline (indicator 3) at five regions along the study area (Fig. 7). Three of them are located in the north half of the island (Canal Zone and North Pond) and the other two to the south (S-Curves). The former three vulnerable spots are located at sections in which the road is convex to the shoreline; they tend to expand in the latitudinal direction and to become more persistent over time. The southern two regions show very different behavior, one occurring only in 2013 and later mitigated by the beach nourishment project, and the other in the south end of the PINWR that has met this vulnerability criterion for the whole 8 years.

**Composite Vulnerability Criteria**

Fig. 7(e) indicates that the least vulnerable transects (in green) occur where the road is far enough from both shorelines and the dune field tends to be well-developed and vegetated. The least vulnerable regions are located near the pocket of the terminal groin (north of the Canal Zone), the center of the Old Sandbag Area, and the appropriately named Stable Zone. For the remaining colors, the warmer the color is, the more vulnerable a transect is. Overall, three areas have been more vulnerable than the rest of the island; they are distributed in the Canal Zone, New Inlet, and S-Curves.

In the whole study area, only two regions (composed of at least two transects) have reached the maximum vulnerability criteria. The transects in those regions are shown in Fig. 7(a) and in detail in Fig. 8. As previously mentioned, the island width indicator is affected by the hydraulic connectivity between the sound and estuarine ponds through narrow channels. As indicated in Fig. 8, both areas experienced overwash during Hurricane Sandy in 2012, after this year the dune crest vulnerability criterion remained constant.

As shown in Fig. 8(a), the island width and the critical buffer are very close to their criteria threshold. As a result, relatively small changes in the ocean shoreline have created an intermittent behavior of indicators 1 and 3 between 2014 and 2018. Areas that have increased the number of indicators over time include the middle of the Canal Zone, the south end of the North Pond (in which the PINWR visitor center is located), the historical location of New Inlet (the star in Fig. 7), and the Rodanthe Breach region within the S-Curves zone.

The validity of the vulnerability indicators was evaluated by comparing the areas that have been predicted to be vulnerable against the areas in which NCDOT reported road impacts and expenses related to sand removal and repairs from winter storms and hurricanes from 2011 to 2016 (Table 2). Overall, every year, NCDOT removed sand or repaired the road in the Canal Zone and the S-Curves. Similarly, in the New Inlet region, NCDOT has completed repairs every year with the exception of 2015. A portion of the road along the Old Sandbag Area required repairs after Hurricane Sandy in 2012. On the other hand, the portions of the roadway within the North Pond and the Stable Zone did not require sand removal nor road repairs due to storms. These reports clearly match the composite vulnerability indicators, in which the Canal Zone, New Inlet, and S-Curves region were identified as the most vulnerable regions.

**Predicted Vulnerability (2020–2030)**

The first step to predict vulnerable locations by the year 2030 was to compute the shoreline positions at each transect into the future.
The panels on the right side of Fig. 9 give an overview of the computation of the shoreline position and change rate, which is the slope of the linear trend generated from the distance to the offshore baseline (i.e., shoreline position) and time. The second panel from left to right in Fig. 9 illustrates the variability of shoreline change rates along the PINWR. The variability in the prediction intervals (third panel from left to right in Fig. 9) is explained not only by the number of shorelines available per transect, but by the variability in the shoreline positions. The largest, smallest, and average half prediction intervals are $69 \text{ m}$, $22 \text{ m}$, and $38 \text{ m}$, respectively. As discussed in the section “Prediction of Highway Vulnerability,” given the magnitude of these values, it is reasonable to assume that the prediction intervals can account for the shoreline response to local sea level rise by the year 2030.

Road vulnerability was computed by predicting the expected position of the shoreline every two years until 2030. Then, areas in which the high erosion shoreline would encroach on the 70-m buffer (230-ft critical buffer) and in which the island width will become less than 305 m were identified. Fig. 10 shows the evolution of those predictions over time starting in 2020 until 2030. Overall, predictions are consistently indicating five vulnerable regions that tend to propagate laterally over time: (1) the Canal Zone, (2) the southern half of the North Pond, (3) the southern half of the Old Sandbag Area, (4) New Inlet, and (5) the S-Curves (Table 3).

As summarized in Table 3, from 2020 to 2030, the length of the predicted vulnerable road in the Canal Zone is 2.4 km. In the southern halves of the North Pond and the Old Sandbag Area, the length of vulnerable road is predicted to increase by 503 m.
and 640 m from 2020 to 2030, respectively. In New Inlet, the vulnerable roadway can potentially increase by 320 m. The S-Curves have the longest stretch of roadway predicted to be vulnerable in the next 11 years, with more than 2.4 km of potentially vulnerable road starting in 2020 and extending to 2.7 km by 2030. Predictions based on future shoreline positions and two vulnerability criteria indicate that 1,692 m of roadway could potentially become vulnerable from 2020 to 2030, resulting in nearly 9 km of vulnerable roadway out of the 20 km analyzed.

Starting in 2020, three regions (i.e., south end of the Canal Zone and two regions in the S-Curves) could simultaneously meet the critical buffer and the island width criteria. Although dune crest elevations are not forecasted, results in Fig. 7 indicate that these regions have had low-dune elevations in previous years, making

![Fig. 10](image-url)

Fig. 10. (Color) Road vulnerability projected every 2 years until 2030 based on predicted shoreline positions, and critical buffer and island width criteria. (a) critical buffer is past 2030 predicted high-erosion shoreline; (b) island width between estuarine shoreline and high-erosion ocean shoreline is less than 305 m; and (c) serious erosive scenario in which 2030 low-erosion ocean shoreline is west (landward) of buffer line and island width is less than 305 m. [Aerial images (a–c) courtesy of NCDOT.]
them the most vulnerable sections of the roadway in the next 10 years. These three regions account for 1.4 km of roadway.

### Discussion

Having infrastructure built in dynamic environments such as barrier islands comes with maintenance and planning challenges that require careful consideration of past, present, and future conditions of both the island and the infrastructure. In the case of the NC 12 highway, data collected as part of the CMP from 2010 to 2018 are being used to determine the vulnerability of the road to long-term erosion, overwash, flooding, and barrier island breaching. As of 2018, the three vulnerability indicators used in this study and the shoreline predictions indicate that there are at least five vulnerable areas distributed along the PINWR, with the exception of the Stable Zone. Of those regions, the Canal Zone, Old Sandbag Area, and north of Rodanthe have been identified as erosional hotspots by previous studies (Hapke and Henderson 2015; Overton and Fisher 2004). In the Stable Zone on the other hand, the vulnerability of the road is diminished by a wide island and a mature and wide foredune region.

As proposed by Pennison et al. (2018b), coastal infrastructure sustainability and resiliency needs reimagining fundamental system requirements to integrate local community desires and roadway functionality. In this line and informed by the vulnerability information from this study and other historical records, NCDOT has begun assessing a variety of options for the long-term retention of the NC 12 highway south of Oregon Inlet (Fig. 11).

The bridge crossing Oregon Inlet, shown in yellow in the right side of Fig. 11, is the new Marc Basnight Bridge that opened to traffic in February 2019. NCDOT has also begun construction of a new bridge that bypasses the S-Curves north of Rodanthe (yellow line in the left side of Fig. 11), in which barrier island breaching has destroyed the road in previous years. This bridge is expected to be completed by 2021. In 2017, NCDOT completed construction of an interim bridge that extends over the inlet opened during Hurricane Irene in 2011 (Pea Island Breach). Options for the sections of highway between these bridges include (but are not limited to) beach nourishment combined with dune construction, relocation of the existing roadway, and additional bridging alternatives. The timing of these future phases will be based on the vulnerability forecasts provided by this study.

The continuous update of shoreline positions and the use of a 95% prediction interval are some of the strengths of this study. Having new data every year and considering worst case (high erosion) potential future shoreline positions, rather than a simple linear trend line, is a conservative approach to indirectly account for the effects of phenomena that may affect the vulnerability of the road. As more data points are added to the data set, it will indirectly include the effects of potential acceleration of sea level rise rates and future extreme events. Quantification of specific uncertainty in shoreline position projections due to sea level rise is beyond of the scope of this paper, but it is acknowledged that when projections extend over multidecadal time scales, sea level rise could account for more than 20% of the variance in shoreline change predictions (Le Cozannet et al. 2019). Potential human induced changes (e.g., beach nourishment, road realignment and relocation, and dune replenishment) cannot be predicted; however, as changes to the road are made, the location of the 70-m critical buffer can be changed, and vulnerability indicators reevaluated.

In addition to the three main vulnerability indicators, as the CMP continues, other morphological variables are monitored and are being considered as potential additional indicators. Such variables include dune toe position and elevation, beach width, volume above mean high water from the edge of pavement to shoreline, and land cover. Hopper and Meixler (2016), Wamsley et al. (2015), and Gornitz et al. (1994) have identified some of these and other variables as useful vulnerability metrics for coastal infrastructure, however, threshold values that could lead to direct road damage have not been defined yet and are currently under evaluation.

The three vulnerability indicators for coastal highways presented in this study can be extended to other regions and types of infrastructure. For regions in which systematic monitoring programs are not in place, the computation of the indicators can be completed from available multitemporal aerial images and elevation data (e.g., LiDAR, Digital Terrain Models) generated by national or state agencies. For smaller regions, a more practical option is the use of imagery and elevation data gathered from unmanned aerial systems, which have proven to provide accurate elevation

### Table 3. Summary of total roadway length (m) predicted to be vulnerable from year 2020 until 2030

<table>
<thead>
<tr>
<th>Year</th>
<th>Canal zone</th>
<th>Southern half of the North Pond</th>
<th>Southern half of the Old Sandbag Area</th>
<th>New inlet</th>
<th>S-curves</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>2,515</td>
<td>1,234</td>
<td>640</td>
<td>549</td>
<td>2,469</td>
<td>7,407</td>
</tr>
<tr>
<td>2022</td>
<td>2,469</td>
<td>1,326</td>
<td>869</td>
<td>640</td>
<td>2,560</td>
<td>7,864</td>
</tr>
<tr>
<td>2024</td>
<td>2,469</td>
<td>1,463</td>
<td>1,052</td>
<td>686</td>
<td>2,606</td>
<td>8,275</td>
</tr>
<tr>
<td>2026</td>
<td>2,469</td>
<td>1,554</td>
<td>1,143</td>
<td>732</td>
<td>2,697</td>
<td>8,595</td>
</tr>
<tr>
<td>2028</td>
<td>2,469</td>
<td>1,554</td>
<td>1,234</td>
<td>777</td>
<td>2,743</td>
<td>8,778</td>
</tr>
<tr>
<td>2030</td>
<td>2,469</td>
<td>1,737</td>
<td>1,280</td>
<td>869</td>
<td>2,743</td>
<td>9,098</td>
</tr>
</tbody>
</table>

© ASCE 04021003-13 Nat. Hazards Rev.

![Fig. 11. (Color) Conceptual alignments for bridges along NC12 in PINWR. (Modified from NCDOT 2017.)](image-url)
information in coastal environments via structure from motion techniques (Gonçalves and Henriques 2015; Scarelli et al. 2017). It should be noted, that local morphological and oceanographic conditions and historical road damage records could lead to variations in the thresholds presented here, for example, Pennison et al. (2018a) state that road alignments within 150 m of the ocean shoreline have significant damage potential for the County Road 257 in Brazoria County, Texas.

The indicators presented in this study can also be used to assess the vulnerability of other types of infrastructure such as power lines, houses, and buildings. However, modifications or additional indicators may be required depending on the elevation and design of a particular structure. Based on the three indicators, the main factors to take into consideration are the distance of the structure to both shorelines, and the protective elevation of natural or man-made infrastructure (e.g., dunes, dikes, barriers) relative to the lowest portion of the structure that could suffer damage and the likely wave runup elevation.

Conclusions

A framework to describe the spatiotemporal vulnerability of roadways on barrier islands was proposed. The use of morphological indicators and shoreline change predictions, including prediction intervals, was proven as a relatively simple, yet reliable strategy to identify vulnerable areas and inform transportation agencies. A case study and a long-term monitoring program along a portion of the NC 12 highway were detailed to provide an example of strategic planning for a coastal roadway.

The spatiotemporal variability of the vulnerability of a coastal highway was assessed via three morphological indicators: (1) island width <305 m, (2) dune crest elevation <3 m above the highway, and (3) edge of pavement within 70 m of the shoreline.

Regions found to be vulnerable according to indicators 1 (island width) and 3 (distance from shoreline to edge of pavement), and the shoreline predictions tend to be localized and to remain vulnerable for the period analyzed (2010–2018). Indicator 2 (dune crest elevation above highway) is the most variable in both time and space. This behavior is a response of the continuous changes in dune height due to the natural erosive processes driven by wave and wind, and the anthropogenic actions that include sand piling and dune rebuilding. Overall, the different vulnerability criteria have been met at regions that have experienced breaching, overwash, and dune erosion during the period analyzed in this study. This correspondence proves the accuracy of the vulnerability indicators and their applicability for large-scale monitoring and planning.

It should be noted that the indicators presented here serve as a first-order assessment to identify potential vulnerabilities, but they cannot guarantee damage to the system. Infrastructure may still be damaged in areas in which indicators are not met. This could be the case when the vulnerabilities are caused by factors not included in this analysis, such as severe rainfall, elevated groundwater levels, or future extreme events triggered by climate change. Moreover, the level of uncertainty for the damage of infrastructure is not computed here, thus, probabilistic approaches should be employed to estimate such uncertainties.

Data from the CMP and vulnerability indicators continue to inform NCDOT about morphological changes in the barrier island that can potentially affect the maintenance and operability of NC 12. Accordingly, NCDOT has begun taking adaptation actions, which include design and execution of new elevated roadway alignments as well as the assessment of other options for the long-term retention of the highway. This case study exemplifies the relevance of systematic monitoring of critical infrastructure to support decision making in highly vulnerable coastal regions.

Future work will continue to add information into the long-term coastal monitoring program and can provide a framework for continuous evaluation of indicators and adaptation as necessary. As 2030 approaches, target years for shoreline prediction will be modified to provide at least a 10-year window for such future predictions. Given the evolving nature of the CMP, potential changes in vulnerability indicators may be required in the future as climate change brings more extreme events to the region and as the roadway alignment evolves. Additional efforts outside the CMP include exploration of road vulnerability due to inlet-related processes.

Data Availability Statement

Some or all data, models, or code used during the study were provided by a third party (e.g., aerial images). Direct requests for these materials may be made to the provider as indicated in the Acknowledgments.

Acknowledgments

The authors would like to thank all the graduate and undergraduate students that have been part of the NCSU-Kenan Natural Hazards Mapping Program for their contributions to build the long-term data sets used in this study. Naming each of the many students who contributed to the terminal groin monitoring and historical data collection efforts would be too lengthy, but their efforts were indispensable. We would like to recognize those students who have worked on the CMP since its inception in 2010: Ross Oliver, Kristin Caracappa, Zachary Kemak, Russell Nasrallah, and Michael Dunn. The authors are grateful to the North Carolina Department of Transportation for providing the funds and remotely sensed data to conduct this study and with Dr. Bret Webb for his thoughtful comments and suggestions to enhance this paper.

Disclaimer

The contents of this paper reflect the views of the author(s) and not necessarily the views of the University. The authors are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the North Carolina Department of Transportation or the Federal Highway Administration at the time of publication. This report does not constitute a standard, specification, or regulation.

References


