National Park Service
U.S. Department of the Interior

Park Facility Management Division - Environmental Management Branch
Park Facility Management Division - Facilities Planning Branch

Outer Banks (OBX) Group

Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment
Updated May 2018

Program for the Study of Developed Shorelines
Western Carolina University
Cullowhee, NC 28723

This document has been developed by the National Park Service Park Facility Management Division (Facilities Planning Branch and Environmental Management Branch – Sustainable Operations Program), in partnership with Western Carolina University, through a Task Agreement with the Southern Appalachian Cooperative Ecosystems Studies Unit. Contributing authors: Katie Peek (kmcdowell@wcu.edu), Blair Tormey (btormey@wcu.edu), Holli Thompson (hthompson@wcu.edu), Robert Young (ryoung@wcu.edu), Shawn Norton (shawn_norton@nps.gov), Julie McNamee (julie_thomas_mcnamee@nps.gov), and Ryan Scavo (ryan_scavo@nps.gov).

Cover Photo: Bodie Island Lighthouse at CAHA (Photo credit: Program for the Study of Developed Shorelines at Western Carolina University).

This Page: Beach and Highway 12 at CAHA (Photo credit: Program for the Study of Developed Shorelines at Western Carolina University).

NPS 910/154048, May 2018

Contents

Please cite this report as: Peek, K.; B. Tormey; H. Thompson; R. Young; S. Norton; J. McNamee; R. Scavo. May 2018. Outer Banks (OBX) Group: Cape Hatteras National Seashore (CAHA), Wright Brothers National Memorial (WRBR), & Fort Raleigh National Historic Site (FORA) Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment. NPS 910/154048. National Park Service, Washington DC.

Executive Summary

The National Park Service (NPS) and Western Carolina University's (WCU) Program for the Study of Developed Shorelines (PSDS), have developed a **Coastal Hazards and Sea-Level Rise Asset Vulnerability Assessment Protocol**. This protocol assesses the vulnerability of infrastructure to multiple coastal hazards and climate change factors over a 35-year planning horizon (to the year 2050). The overall goal is to standardize the methodologies and data used, allowing managers to compare the vulnerability of coastal assets across local, regional, and national levels. This protocol is also designed to accommodate regional differences in coastal hazards (e.g., storm surge vs. tsunami), geomorphology, evolving data sets, and scientific understanding of hazards.

Unlike natural resource vulnerability, which commonly combines three metrics (exposure, sensitivity, and adaptive capacity), the protocol assesses infrastructure using exposure and sensitivity to coastal hazards and sea-level rise to derive a vulnerability score, with adaptation strategies discussed qualitatively in the context of that score.

A total of 266 structures and 202 transportation assets were included in the vulnerability assessment in the Outer Banks Group (OBX) of national parks, which includes Cape Hatteras National Seashore, Wright Brothers National Memorial, and Fort Raleigh National Historic Site. Over two-thirds of all OBX assets analyzed have either a high or moderate exposure ranking, while nearly one-third have either low or minimal exposure. Most OBX assets have moderate sensitivity, and approximately one-quarter have high sensitivity. No OBX structures or transportation assets have low sensitivity.

The majority of OBX assets are either high or moderate vulnerability to coastal hazards and sea-level rise. Only 12% of OBX assets have low vulnerability, while 19% of assets have minimal vulnerability, meaning that they do not fall within any of the exposure hazard zones. A higher percentage of transportation-related assets have high vulnerability compared to structures.

High priority structures that also have a high vulnerability include the Visitor Center/Double Keepers Quarters at Bodie Island and the Ocracoke Island HS Keepers Quarters. In addition, 40% of structures with a current replacement value over $1 million are highly vulnerable. The highly vulnerable transportation assets at OBX are primarily comprised of roads and parking lots. High priority transportation assets that are also highly vulnerable include the Hatteras Inlet Pole and Cable Crossing Roads and the boardwalks at Ocracoke Day Use Overlook and Coquina Beach. Combined, the high vulnerability transportation assets have a replacement value of over $182 million.

Vehicle access to many assets at OBX is dependent on NC Highway 12, the primary road that runs along the barrier islands. NPS owns the first seven miles of Highway 12 (from Whalebone Comfort Station to Bodie Island Maintenance), and the remaining portions are owned by the State of North Carolina. However, all sections of the road within the park boundary are included in the NPS facilities database, and NPS can maintain this asset if necessary. For this analysis, the portion of Highway 12 within the NPS boundary was divided into 14 segments. Results show that 75% of these segments (>36 miles) have high vulnerability. If this transportation corridor becomes impassable due to coastal hazards, visitor access to hundreds of assets (by road) would be severely limited.

Vulnerability Assessment Products & Deliverables

1. Excel datasheets: All results are provided in tables, including asset-specific scoring. The exposure, sensitivity, and vulnerability scores are reported alongside the Facilities Management Software Systems (FMSS) data for each asset, as well intermediate scores in the analysis.

2. Geographic Information Systems (GIS) Maps and Layers: WCU will provide all GIS data, including the exposure layers, exposure results, and final vulnerability results to the park as a separate file. The GIS data will also be available to view online at the NPS ArcGIS Online website. Digital data sources can be found in the next section of this document. Contact WCU or NPS for further information.

3. Park Specific Vulnerability Results Summary Document: This summary document (herein) explains the deliverables, results, and methodology. It briefly summarizes the vulnerability assessment results in the aforementioned datasheets and maps, as well as the methodology, which has been vetted and approved by NPS. This document does not fully describe all results from the analysis; see provided datasheets for detailed results.

Digital Data Sources

1. FEMA Flood Zones: FEMA flood maps were obtained from the FEMA's National Flood Hazard Layer (Official) on ArcGIS.com. According to FEMA, the VE zones are areas subject to inundation by the 1-percent-annual-chance flood event, with additional hazards due to storm-induced velocity wave action, and the AE zones are areas subject to inundation by the 1-percent-annual-chance flood event (determined by detailed methods).

2. Sea-Level Rise – Climate Change Response Program (CCRP): Sea-level rise data for the year 2050 were provided by the NPS CCRP (access report here). WCU utilized the 2050 sea-level rise inundation model (IPCC 8.5 Representative Concentration Pathway).

3. Storm Surge (SLOSH) – Climate Change Response Program (CCRP) – Storm surge data were provided by NPS CCRP (access report here). These data were provided to WCU as a geodatabase by CCRP, and WCU utilized the C3M_km3, which represents a category 3 mean tide surge model. The shapefile was further edited by WCU to only show area of inundation.

4. Erosion/Coastal Proximity - Erosion rate data were acquired from North Carolina's Division of Coastal Management. Where available, rates were utilized to make buffer zones for a 35-year time frame (2050). Rates were binned into the following categories before buffering: 1m/year, 2m/year, 4m/year, 6m/year, 8m/year, etc. (increments of 2 meters). For shorelines without erosion rate data (ocean or estuarine) a simple coastal proximity buffer of 35 meters was applied. The erosion rate buffers and the proximity buffers combined comprise this exposure indicator zone for OBX. The shoreline was digitized using ESRI streaming layer at scale of 1:2500.

Introduction & Project Description

The National Park Service (NPS) and Western Carolina University's (WCU) Program for the Study of Developed Shorelines (PSDS), have developed a **Coastal Hazards and Sea-Level Rise Asset Vulnerability Assessment Protocol**. This protocol establishes a standard methodology and set of best practices for conducting vulnerability assessments in the built environment.

Standardizing the methodologies and data utilized in these assessments allows managers to compare the vulnerability of coastal park assets across local, regional, and national levels. This includes the standardization of data inputs (i.e. widely available, established data) that will allow the application of a consistent methodology among units. Another goal is to create a more complete and effective set of indicators for assessing the sensitivity of assets to coastal hazards. The focus for this protocol is on structures (buildings) and transportation assets in the NPS asset database (Facilities Management Software System; FMSS), but it could be adapted to other resources. The term "asset" is used in this document to represent any structure or transportation infrastructure listed in FMSS, regardless of ownership.

A standardized approach to assessing climate change vulnerability was proposed in a multiple agency document titled "Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment (Glick et al., 2011)." This document defines the vulnerability of natural resources to climate change as: the extent to which a species, habitat, or ecosystem is susceptible to harm from climate change impacts. Vulnerability under this approach is comprised of three equally weighted metrics or components: exposure, sensitivity, and adaptive capacity:

Vulnerability = Exposure + Sensitivity + Adaptive Capacity

- ✓ **Exposure** refers to whether a resource or system is located in an area experiencing direct impacts of climate change, such as temperature and precipitation changes, or indirect impacts, such as sea-level rise.
- ✓ **Sensitivity** refers to how a resource or system fares when exposed to an impact.
- ✓ **Adaptive Capacity** refers to a resource's or system's ability to adjust or cope with existing climate variability or future climate impacts.

While this methodology has been successfully applied to natural systems, some aspects are less appropriate for application in the built environment (i.e., buildings, roads, etc.). For example, structures cannot inherently adapt to climate change or other hazards, while natural resources often can (a salt marsh can adapt to sea-level rise by migrating upland, whereas a building cannot). Therefore, NPS and WCU have modified the methodology and formula for conducting vulnerability assessments of infrastructure within national parks. The modified formula for the vulnerability of the built environment (buildings, transportation assets, etc.) is:

Vulnerability = Exposure + Sensitivity

For this methodology, adaptive capacity of an asset is evaluated separately and is not included in the vulnerability score. This does not mean that understanding the adaptive capacity of an asset is not important. Identifying the range of effective adaptations for key vulnerable assets is the final and most important step in the overall analysis. Effective adaptations will reduce exposure and/or sensitivity, which is the key to reducing vulnerability.

General Protocol Methodology

The **Coastal Hazards and Sea-Level Rise Asset Vulnerability Assessment Protocol** has four primary steps: 1) Exposure Analysis and Mapping, 2) Sensitivity Analysis, 3) Vulnerability Calculations, and 4) Adaptation Strategies Analysis. A detailed description of the protocol can be found in the final section of this document: Vulnerability Assessment Methodology. Further scoring information can also be found in the Excel results sheets that accompany this report. Below is a general description of the first three steps of the protocol.

Exposure Analysis and Mapping: Standard exposure indicators have been established as part of this protocol (Table 1); these indicators represent the primary factors that should be evaluated to determine an asset's coastal hazard and sea-level rise exposure (to the year 2050). The exposure analysis uses data imported into a Geographical Information System (GIS), as exposure is directly dependent on location relative to mapped hazard data. Assets located within an exposure indicator hazard zone (e.g., storm surge hazard zone) are assigned a higher score than assets located outside the zone. Scores for each indicator are then summed and binned to get a total exposure score. Final exposure scores fall into one of four ranking categories (based on the number of exposure zones): minimal exposure (asset does not lie within any mapped zone), low exposure (1 zone), moderate exposure (2-3 zones), and high exposure (4-5 zones).

Table 1. OBX specific hazards and data sources for the exposure indicators.

Exposure Indicator	OBX Specific Hazard	OBX Data Source
Flooding Potential	1% annual flood ± velocity/waves	FEMA Flood Zones (VE or AE)
Extreme Event Flooding	Storm Surge	NPS-specific SLOSH* modeling
Sea-Level Rise Inundation	2050 sea-level rise	NPS-specific SLR modeling
Shoreline Change	Erosion & coastal proximity	NC DCM erosion rates & proximity buffers
Reported Coastal Hazards	Historical flooding	Park questionnaire; storm reports; park visit

*SLOSH - Sea, Lake, and Overland Surges from Hurricanes

Sensitivity Analysis: Sensitivity is a function of the inherent properties or characteristics of an asset. Primary indicators have also been determined for asset sensitivity: flood damage potential, storm resistance, physical condition, historical damage, and protective engineering. The main data source for much of the sensitivity analysis is an asset-specific questionnaire (completed by park staff), which contains detailed questions related to each of the sensitivity indicators. A higher score is given for an unfavorable sensitivity indicator result (e.g., an asset built at grade will get a high score for flood damage potential). The sensitivity scores for each indicator are summed to obtain a total raw score, then binned into three categories: low, moderate, and high sensitivity. Because an asset must be exposed to a hazard in order to be sensitive to it, assets with minimal exposure are excluded from the sensitivity analysis.

Vulnerability Calculation: To calculate a vulnerability score for each asset, the exposure and sensitivity scores are summed, and then assigned to four vulnerability ranking categories. The vulnerability ranking categories are as follows: minimal (assets with minimal exposure), low, moderate, and high.

Unique Factors & Considerations

Geomorphologic Challenges

The OBX has a unique set of geomorphic challenges for conducting a vulnerability assessment. A significant portion of assets are located along rapidly changing barrier island shorelines (most of the national seashore). Both the sea-level rise and storm surge models utilize data that represent a snapshot in time of the shoreline position and elevations within the park. In some locations, the raw data sources may be several years old, and can quickly become outdated as the barrier island migrates and changes. This is especially true if the area experiences major erosion or storms, as these events can completely reconfigure a barrier island's shoreline and topography.

Due to the dynamic barrier island environments of the OBX and the constant migration of the shoreline, there were some assets that clearly should be included in the surge and/or sea-level rise zones (but were not in the original raw data). In these cases, WCU used professional judgment and geological knowledge of the area to make changes to the results for exposure. These changes were primarily for assets such as piers, pier houses, and docks that are already near or within the water, and therefore, should be included in both the sea-level rise and surge zones (Figure 1). Notes about these changes can be found within the exposure tab of the results excel sheets.

OBX Roads

Due to the barrier island nature of the park, several of the roads in the OBX region are long and linear. In order to acquire sensitivity data for these roads, a few were divided into segments; these segments were based on several factors, primarily exposure level and connectivity/access to other park assets. For OBX, three roads were divided: NC Highway 12 (two separate entries in FMSS) and Lighthouse Road. Portions of some road segments were both inside and outside of an exposure zone (for example, only part of a road may intersect the FEMA VE zone). In these cases, a judgment call was made using the approximate percentage of the road within the zone, as well as the location of the hazard (if the hazard is only present at the terminus of the road or segment, or if it intersects in the middle of the road).

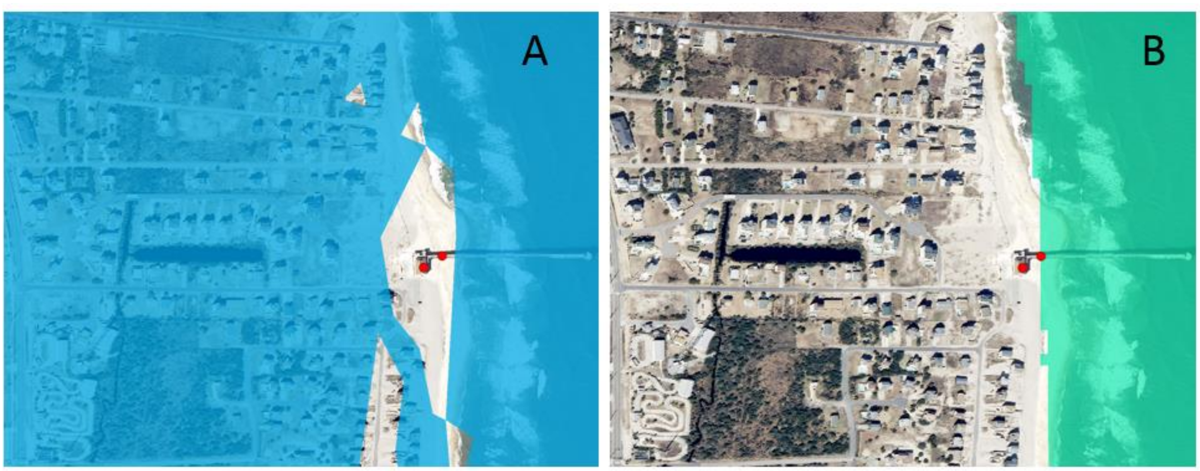

Figure 1. Exposure hazards zones for Rodanthe Fishing Pier and Pier House on Hatteras Island (red dots). A) SLOSH model results (blue shading represents surge inundation). B) 2050 sea-level rise model results (green shading represents sea-level rise inundation). Both assets were given unfavorable scores for the surge and sea-level rise exposure hazards, despite raw data results.

Results Summary & Discussion

A total of **266 structures** (buildings, shelters, monuments, and amphitheaters) and **202 transportation assets** (roads, road segments, parking lots, piers, docks, access ramps, road turnouts, boardwalks/platforms, etc.) were included in the vulnerability assessment of the Outer Banks Group of national parks. ***In this report, Outer Banks Group (herein: OBX) refers to assets within Cape Hatteras National Seashore (CAHA), Fort Raleigh National Historic Site (FORA), and Wright Brothers National Memorial (WRBR)***. Also, the results for this vulnerability assessment represent a time frame of approximately 35 years (to the year 2050). Specific scores for these factors are reported (alongside FMSS data) for each individual asset in the supplied Excel datasheets; final exposure and vulnerability results are also provided as GIS maps and layers.

Exposure Results

A notable result of the exposure analysis at OBX is that most assets (structures and transportation) have a moderate (46%) or high (22%) exposure (Table 2). Although the park is comprised of barrier islands, only a modest percentage of structures have high exposure (12%). These high exposure assets include structures in areas such as Coquina Beach, Frisco Day Use, Ocracoke Day Use, Bodie Island Maintenance, Hatteras Island Rodanthe, and FORA Theater (Figures 2 and 3). The relative lack of high exposure structures is primarily due to the fact that most are located outside the 2050 sea-level rise and erosion hazard zones. In contrast, a larger percentage of transportation-related assets have high exposure (35%). The high exposure transportation assets are typically located on the narrowest portions of the barrier islands, particularly along NC Highway 12 (Figure 3).

Only 12% of OBX assets have low exposure, and a substantial number of assets (19%) have minimal exposure, which means the assets do not lie within **any** of the mapped exposure hazards zones (flooding, storm surge, erosion/coastal proximity, sea-level rise, and historical flooding - see Vulnerability Assessment Methodology section of this document). Exposure is directly dependent on location; thus, if an asset is located beyond the influence of a particular coastal hazard, its exposure is diminished. Most minimal exposure assets are located in the FORA, WRBR, and the Hatteras Island Frisco Campground areas (Figure 2). These areas are all further from coastal waters, higher in elevation, and on more stable portions of the islands. This does not mean that they have **no** exposure to coastal hazards, only that they have a minimal exposure based on the metrics analyzed as part of this study. More structures had a minimal exposure ranking than transportation assets (27% and 9%, respectively).

Table 2. OBX Exposure Results Summary. Sum of percentages may not equal 100 due to rounding.

Assets	High Exposure		Moderate Exposure		Low Exposure		Minimal Exposure		Total #
	#	%	#	%	#	%	#	%	
Structures	33	12%	130	49%	31	12%	72	27%	266
Transportation	71	35%	86	43%	26	13%	19	9%	202
All OBX Assets	**104**	**22%**	**216**	**46%**	**57**	**12%**	**91**	**19%**	**468**

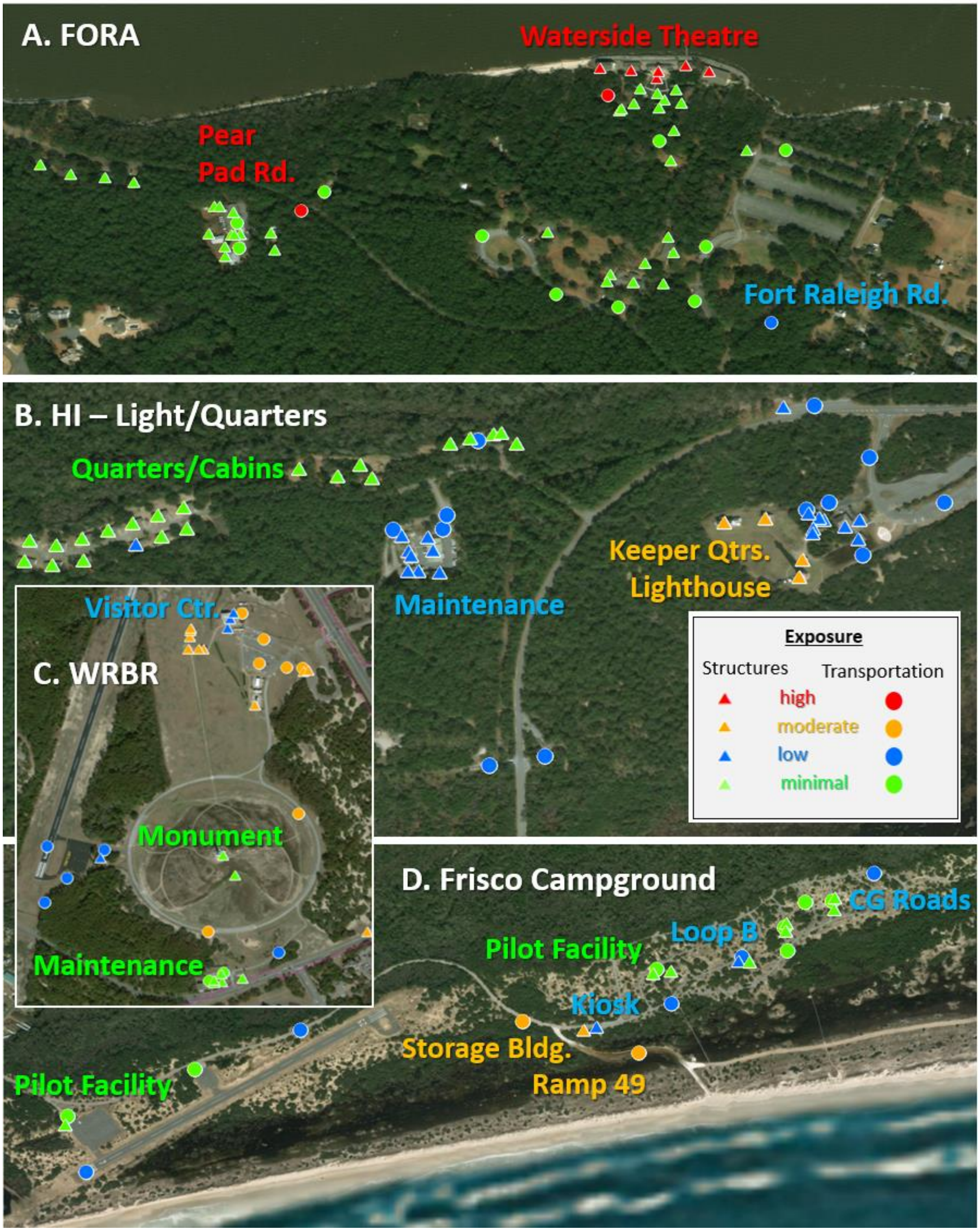

Figure 2. Mapped exposure results for select OBX areas: A) Fort Raleigh (FORA), B) Hatteras Island (HI) – Lighthouse/Quarters, C) Wright Brothers (WRBR), and D) Frisco Campground. Only select assets and areas are labeled, see Excel sheets for the full results. Background is aerial imagery from ESRI streaming layer.

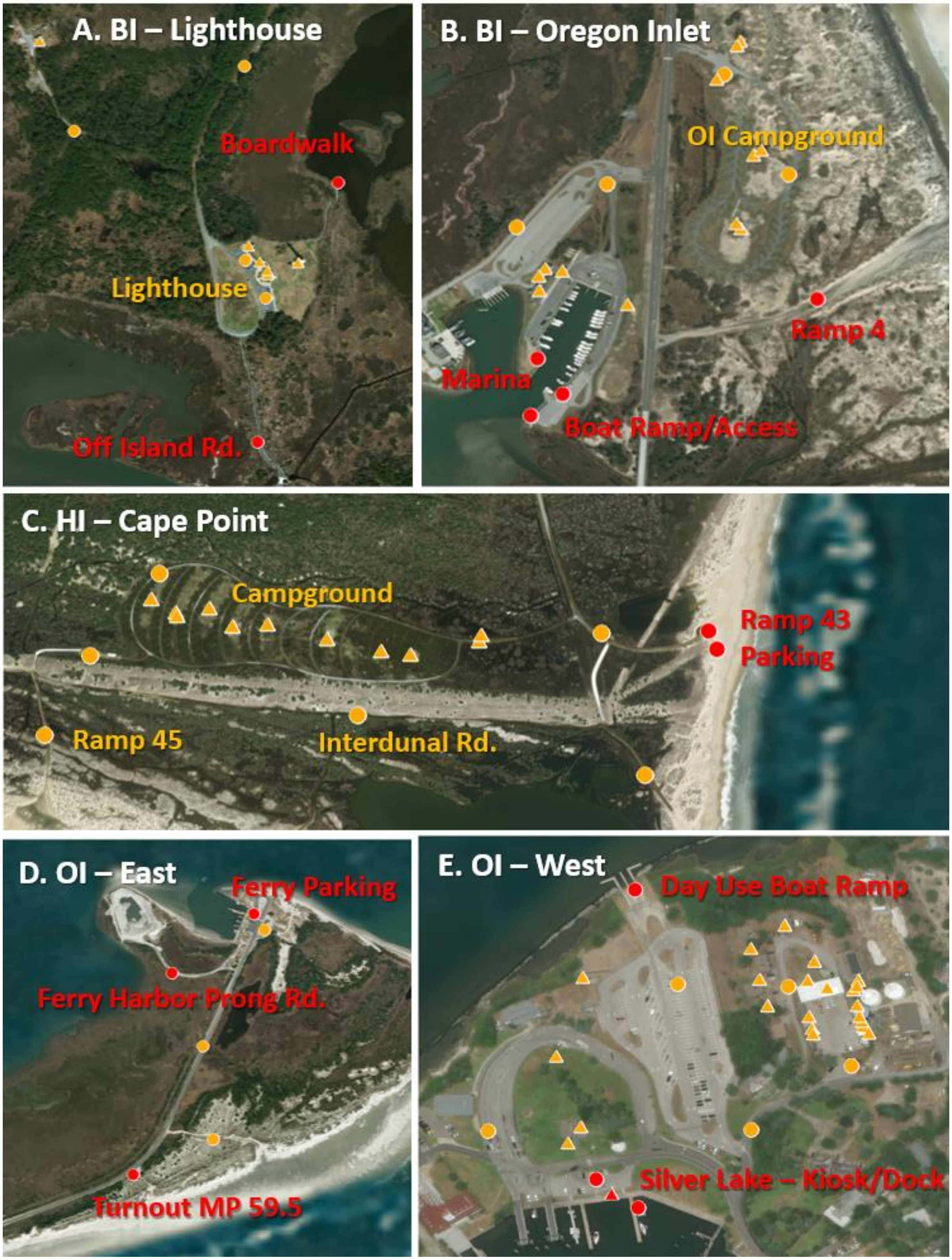

Figure 3. Mapped exposure results for select OBX areas: A) BI – Lighthouse, B) BI – Oregon Inlet, C) HI- Cape Point Campground, D) OI – East End, and E) OI – West End. Only select assets and areas are labeled, see Excel sheets for the full results. Background is aerial imagery from [ESRI streaming layer].

Sensitivity Results

The sensitivity results for all OBX assets (structures and transportation) show the majority (75%) have moderate sensitivity (Table 3). When separated into structures and transportation, the sensitivity scores for OBX assets are slightly different. Most (86%) structures have moderate sensitivity, with only 14% high sensitivity. For transportation assets, a substantial number of assets are high sensitivity (38%). No OBX assets (structures or transportation) have low sensitivity based on this methodology.

Table 3. OBX Sensitivity Results Summary. Sum of percentages may not equal 100 due to rounding.

Assets	High Sensitivity		Moderate Sensitivity		Low Sensitivity		Total # Analyzed	Excluded* (min. exposure)
	#	%	#	%	#	%		
Structures	28	14%	166	86%	0	0%	194	72
Transportation	69	38%	114	62%	0	0%	183	19
All OBX Assets	**97**	**26%**	**280**	**75%**	**0**	**0%**	**375**	91

*Assets with minimal exposure (in no hazard zone) were excluded from the sensitivity analysis. Thus, total # analyzed is different for sensitivity compared to exposure and vulnerability.

The structures that scored unfavorably in all four sensitivity indicator categories include the Pavilion and Hangar Building, Fee Kiosk A and Fee Kiosk B at WRBR, and the Carpenter Shop and Maintenance Shop at Bodie Island. The rest of the high sensitivity structures at OBX have unfavorable scores in three of the four categories (at-grade construction, lack of protective engineering, and either lack of storm resistance or historical flood damage).

Because only a few transportation assets were reported to be elevated (the boardwalks and ramps), and no transportation assets were reported to be storm-resistant, the primary indicator influencing sensitivity was condition. Almost all transportation assets with high sensitivity were reported to be in poor condition, while most assets with moderate sensitivity were reported to be in good condition. The next indicator influencing sensitivity was historical damage, with 53 out of 69 high sensitivity assets having been damaged historically, but only 10 out of 114 moderate sensitivity assets.

First Floor Elevation Data Collection

First floor elevation data collected by the North Carolina Floodplain Mapping Program (NCFMP) were also included in the sensitivity analysis. Ideally, the elevation of all assets would be compared to the Federal Emergency Management Agency's (FEMA) Base Flood Elevation (BFE), and the precise threshold/first floor elevations acquired by NCFMP make this comparison possible. This aided in the determination of more reliable sensitivity indicators for assets at OBX.

The first-floor elevation data verifies the flood damage potential indicator of the sensitivity analysis. This elevation was compared to local BFE for each asset to determine if the primary threshold (first floor elevation) was above or below BFE. In general, if an asset's first floor elevation is above BFE it received a favorable score for the flood damage potential sensitivity metric.

The first-floor elevation data verified the flood damage potential sensitivity metric for 72 of the 266 structures analyzed at OBX (data was not used for transportation assets). Thirty-nine (54%) of the structures analyzed have first floor elevations above local BFE, and 33 have elevations below local BFE. This comparative analysis led to revised scores for the elevation metric (as compared to the original park questionnaire) for 26 structures, all of which were originally reported as not elevated, and were subsequently ***changed to elevated***.

Vulnerability Results

The majority of OBX assets are either high or moderate vulnerability to coastal hazards and sea-level rise (Table 4). Only 12% of OBX assets have low vulnerability, while 19% of assets have minimal vulnerability, meaning that they do not fall within any of the exposure hazard zones. A higher percentage of transportation-related assets are high vulnerability compared to structures (50% and 19%, respectively). However, approximately one-quarter of the high vulnerability transportation assets are beach ramps and soundside access roads. Figures 4 through 8 show the vulnerability results for select areas of OBX.

High priority structures that are also highly vulnerable include the Visitor Center/Double Keepers Quarters at Bodie Island (asset priority index within FMSS, API =100) and the Ocracoke Island HS Keepers Quarters (API = 80). In addition, 40% of structures with a current replacement value (CRV within FMSS) over $1 million are highly vulnerable (13 of 33 assets); these include the Waterside Theater Amphitheater and Waterside Theater Costume Shop at FORA, the Ocracoke Island Maintenance Shop, and the Visitor Center/Double Keepers Quarters at Bodie Island. Combined, the high vulnerability structures have a CRV of over $44 million (18% of the total CRV of structures).

Table 4. OBX Vulnerability Results Summary. Sum of percentages may not equal 100 due to rounding.

Assets	High Vulnerability		Moderate Vulnerability		Low Vulnerability		Minimal Vulnerability		Total #
	#	%	#	%	#	%	#	%	
Structures	51	19%	112	42%	31	12%	72	27%	266
Transportation	101	50%	56	28%	26	13%	19	9%	202
All OBX Assets	**152**	**32%**	**168**	**36%**	**57**	**12%**	**91**	**19%**	**468**

Vehicle access to many OBX assets is dependent on NC Highway 12 (API = 65), the primary road that runs along the barrier islands. NPS owns the first seven miles of Highway 12 (from Whalebone Comfort Station to Bodie Island Maintenance), and the remaining portions are owned by the State of North Carolina. However, all sections of the road within the park boundary are included in FMSS, and NPS can maintain this asset if necessary. For this analysis, the portion of Highway 12 within the NPS boundary was divided into 14 segments. Results show that 75% of these segments (>36 miles) are highly vulnerable (Figure 4). If this transportation corridor becomes impassable due to coastal hazards (which often happens during storms), visitor access to hundreds of assets by road would be severely limited.

The highly vulnerable transportation assets at OBX are primarily comprised of roads and parking lots. High priority transportation assets that are also highly vulnerable include the Hatteras Inlet Pole and Cable Crossing Roads (both API = 77), and the boardwalks at Ocracoke Day Use Overlook and Coquina Beach (both API =70). Combined, the high vulnerability transportation assets have a CRV of over $182 million, which is approximately 70% of all transportation CRV. The segmentation of roads can skew the statistics; for example, of the $182 million in high vulnerability assets, $138 million represents the entire length of the three segmented roads.

Overall, approximately one-third of OBX assets have high vulnerability using this methodology (Table 4, Figures 5 - 8). However, there are several important caveats to the assessment and results:

1) This methodology is meant to assess the vulnerability of a park to multiple coastal hazards and climate change factors combined (i.e., erosion, flooding, storm surge, sea-level rise, and historical flooding; see indicator list in methodology section). Therefore, a park or section of park (like the

narrow portion of the OBX barrier islands) that has maximum exposure to one or more of these factors (i.e., surge) will inherently have a higher overall vulnerability.

2) A major goal of this methodology is to create a standard protocol for vulnerability assessments, regardless of the data utilized. Therefore, as higher quality data become available for the metrics of vulnerability (exposure and sensitivity), the final rankings for these assets may change. In these cases, the same protocol will be used, but new more precise data can be utilized, increasing the reliability of the vulnerability results.

3) Vehicle access to OBX assets also depends on several transportation corridors that are not owned by NPS (e.g., portions of NC Highway 12, Highway 64 through Manteo, Washington Baum Bridge, Virginia Dare Memorial Bridge, and Herbert C. Bonner Bridge). Some low or moderate vulnerability assets could be safe from flooding (and sea-level rise), but rendered completely inaccessible by road. Other coastal parks have similar issues that relate to ownership or jurisdiction of the transportation leading to NPS-owned assets and resources, necessitating coordination (i.e., additional collaborative vulnerability studies) with regional stakeholders, land owners, and partners.

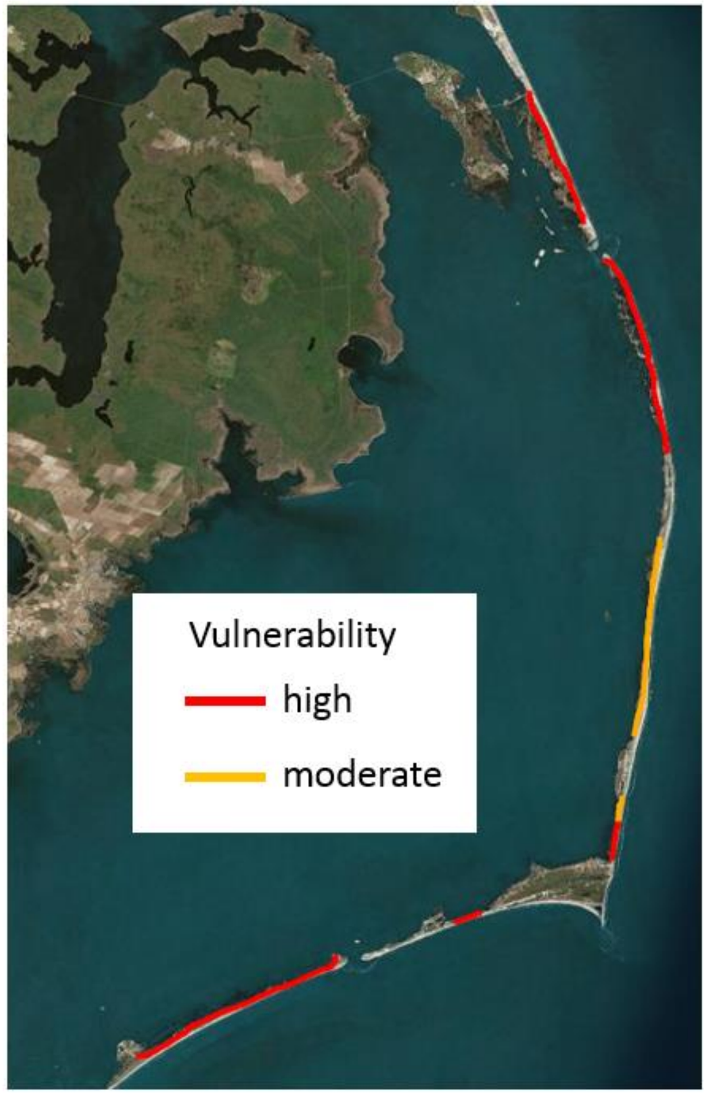

Figure 4. Vulnerability of North Carolina Highway 12 segments within OBX. Background is aerial imagery from [ESRI streaming layer.]

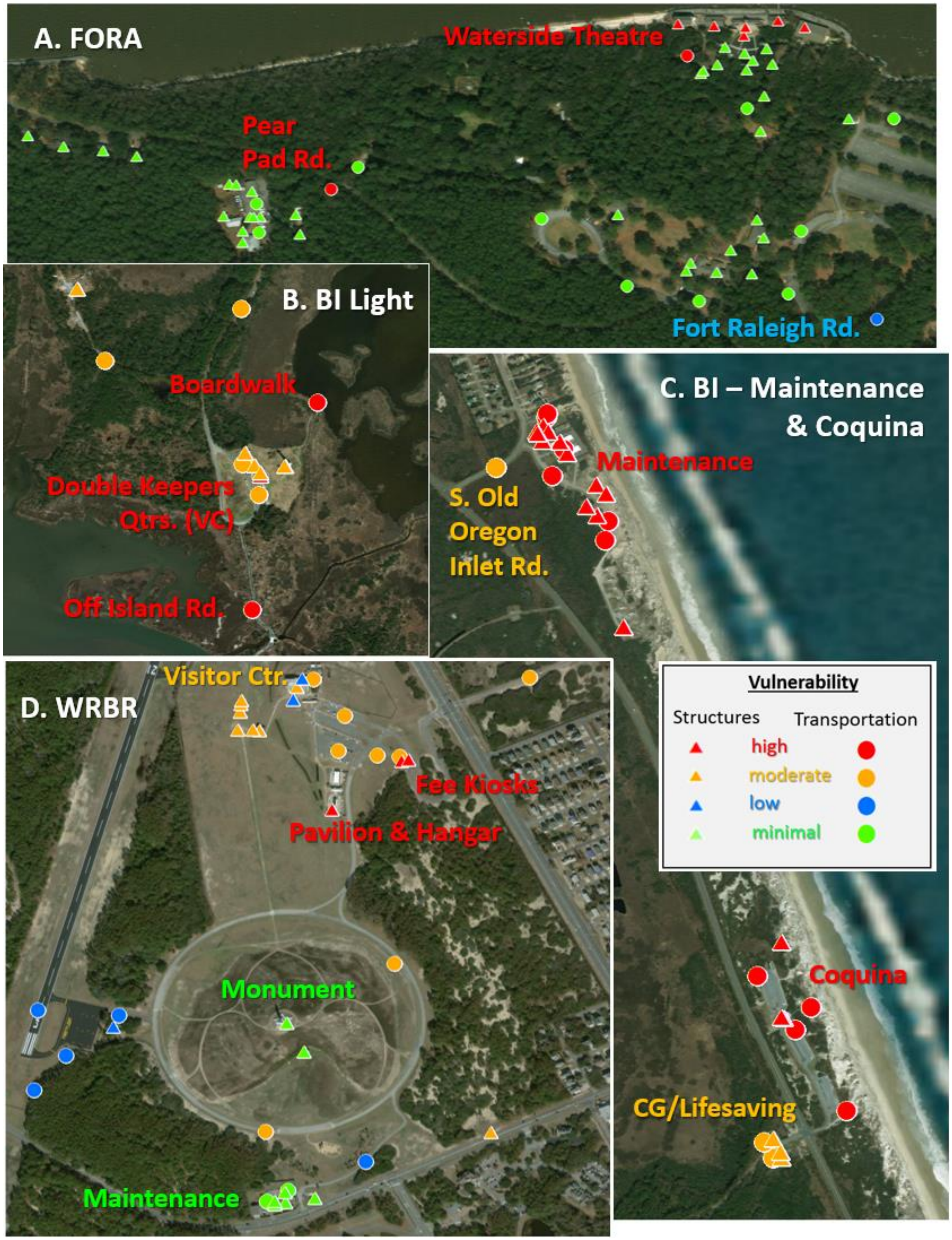

Figure 5. Mapped vulnerability results for select OBX areas: A) Fort Raleigh - FORA, B) BI - Lighthouse, C) BI – Maintenance and Coquina, and D) Wright Brothers - WRBR. Only select assets and areas are labeled, see Excel sheets for the full results. Background is aerial imagery from ESRI streaming layer.

Figure 6. Mapped vulnerability results for select OBX areas: A) BI – Oregon Inlet Fishing, B) HI – Avon, C) Pea Island, and D) HI – Salvo. Only select assets and areas are labeled, see Excel sheets for the full results. Background is aerial imagery from ESRI streaming layer.

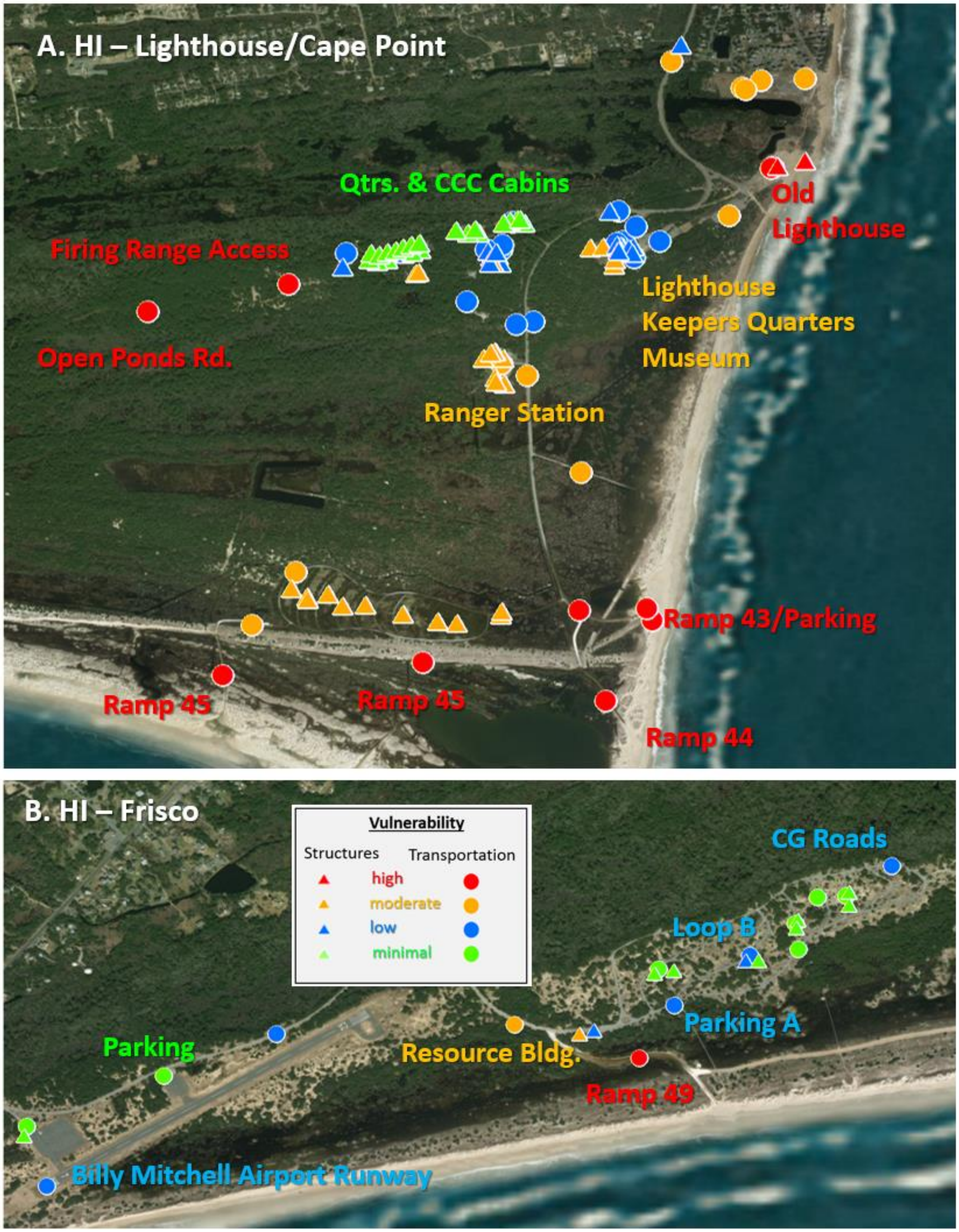

Figure 7. Mapped vulnerability results for select OBX areas: A) HI – Lighthouse/Cape Point and B) HI – Frisco. Only select assets and areas are labeled, see Excel sheets for the full results. Background is aerial imagery from ESRI streaming layer.

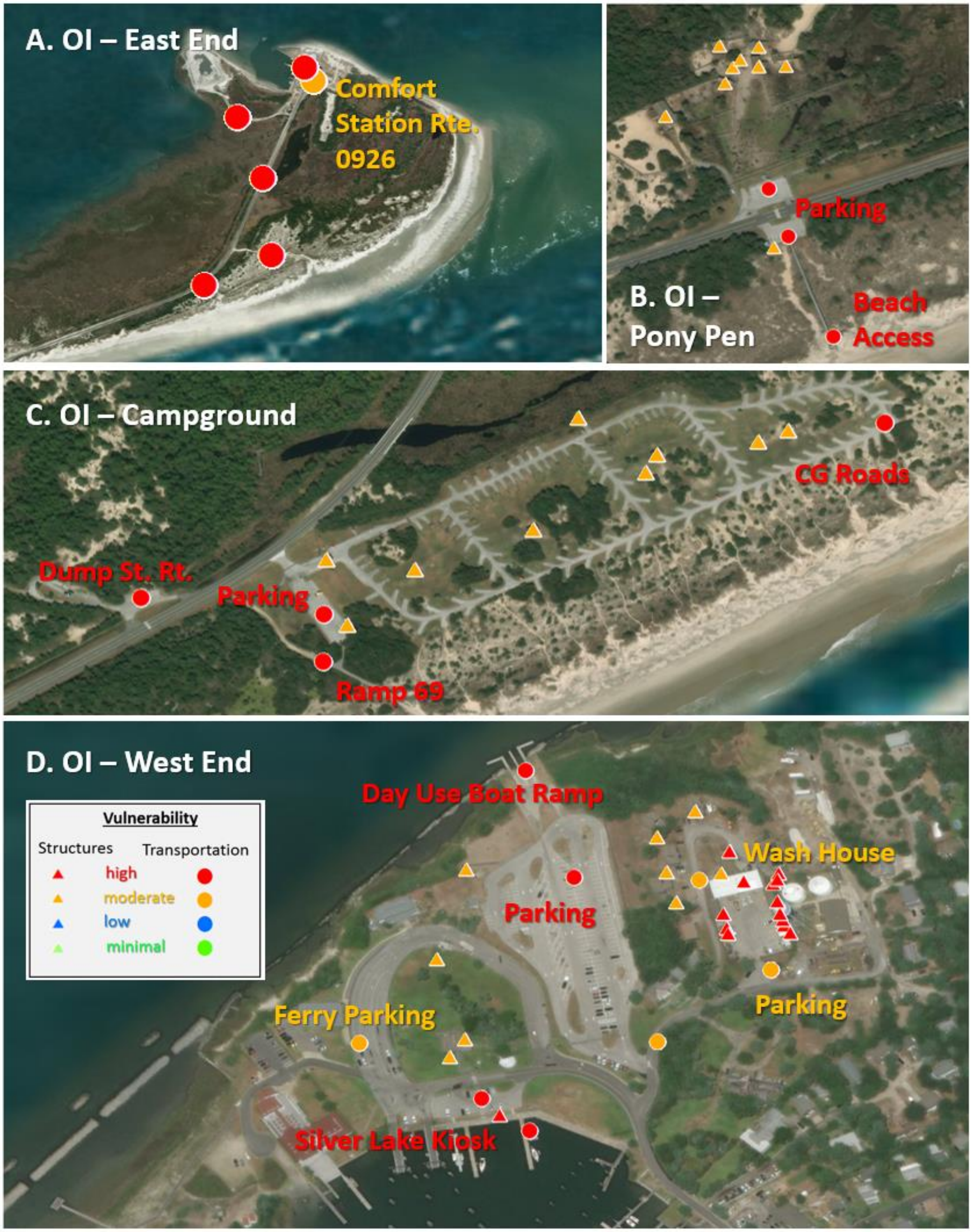

Figure 8. Mapped vulnerability results for select OBX areas: A) OI – East End, B) OI – Pony Pen, C) OI- Campground, and D) OI –West End. Only select assets and areas are labeled, see Excel sheets for the full results. Background is aerial imagery from ESRI streaming layer.

Vulnerability Assessment Methodology

The **Coastal Hazards and Sea-Level Rise Asset Vulnerability Assessment Protocol** has four primary steps:

1) Exposure Analysis & Mapping
2) Sensitivity Analysis
3) Vulnerability Calculation
4) Adaptation Strategies Analysis

Step 1: Exposure Analysis & Mapping

The first step in the protocol is to analyze the exposure of NPS assets to coastal hazards and sea-level rise. Standard exposure indicators have been determined by WCU; these indicators represent the primary factors or hazards that should be evaluated to determine an asset's exposure (to the year 2050). The five general exposure indicators are: flooding potential, extreme event flooding, sea-level rise inundation, shoreline change, and reported coastal hazards. The goal of this methodology is to standardize the data sources for exposure analysis, using widely available and regularly updated sources (when possible). Table 5 summarizes these indicators, as well as common data sources for each.

Table 5. Exposure Indicators for Asset Coastal Hazards and Sea-Level Rise Vulnerability Protocol

Exposure Indicator	Common Data Sources
☑ **Flooding Potential** 1% annual flood chance ± velocity/waves	FEMA Flood Zones (VE or AE); LiDAR DEM or other elevation model
☑ **Extreme Event Flooding** storm surge, tsunami, extreme high water	NPS-specific SLOSH model; tsunami models; tide gage recorded extreme high water data
☑ **Sea-Level Rise Inundation** 2050 projection	NPS-specific SLR modeling; LiDAR DEM or elevation other model
☑ **Shoreline Change** erosion, coastal proximity, cliff retreat	State or USGS erosion rate buffers; cliff retreat rate buffers; shoreline proximity buffers
☑ **Reported Coastal Hazards** historic flooding, visible slope instability	Park surveys/questionnaire results; storm imagery & reconnaissance

The exposure analysis utilizes data imported into Geographical Information Systems (GIS) format, as exposure is directly dependent on location and mapped hazard data (whether the area experiences the hazard). Digital hazard data are gathered for each of the exposure indicators, such as the online georeferenced FEMA flood map layers. The only dataset that does not come from a widely available, well established source is the reported coastal hazards layer, which is derived from storm imagery, reconnaissance, and direct communication with park personnel. Each exposure data layer thus represents an exposure indicator hazard zone for a particular park. Assets that are located within a particular zone are assigned a higher score than assets located outside of the hazard zone.
The following sections describe the specific methods, scoring, and common data sources of each exposure indicator.

Flooding Potential:

The flooding potential indicator describes hazards related to the 1% annual flood chance, including waves and water velocity. For most parks, data for this exposure indicator comes from FEMA's digital flood maps. Two primary FEMA flood zones are utilized: the VE and AE zones (and sometimes the A, AO, or AH). According to FEMA, the VE zones are areas subject to inundation by the 1-percent-annual-chance flood event, with additional hazards due to storm-induced velocity wave action, and the AE zones are areas subject to inundation by the 1-percent-annual-chance flood event (determined by detailed methods). For a further description of the FEMA flood zones, including the other A zones, see FEMA's website.

If an asset is within the AE (or other A) zone, it receives an unfavorable score (4) for the flooding indicator. Any asset within the VE zone (the highest hazard zone) receives an unfavorable score for the flooding indicator, and is also assigned an automatic high score for exposure overall. Assets in neither flood zone receive a favorable score (1) for this indicator. Within some parks the FEMA data is incomplete; in these cases, other elevation data sources (such as LiDAR DEMs) are used to supplement the FEMA data.

Extreme Event Flooding:
The extreme event flooding indicator captures flooding from major storms, tsunami, and other extreme high water events. **Storm surge** is the primary extreme event flooding that occurs within parks along the east and gulf coast of the U.S. The data source for storm surge is a NOAA surge inundation model: Sea, Lake, and Overland Surges from Hurricanes (SLOSH; see NOAA for more information).

The SLOSH model uses a composite of several thousand model runs with differing storm conditions each time to predict surge. There are two products of this: the Maximum Envelope of Water (MEOW), which is a set of worst case scenarios for certain characteristics like storm category, speed, trajectory, and tide level; and the Maximum of the Maximum Envelope of Water (MOM), which is the worst of all potential scenarios modeled. The surge data included in the exposure analysis (the SLOSH MOM for a category 3 storm) represents the maximum potential surge conditions. SLOSH storm surge data for this protocol was supplied by the NPS Climate Change Response Program (CCRP).

For parks that are not subject to tropical storms and surge (primarily west coast parks), an alternative extreme event flooding hazard is evaluated, commonly either modeled **extreme high water** events or modeled **tsunami** hazard zones. Data for extreme high water events were provided by CCRP; these data map historic patterns of extreme high water events based on tide gage information. The source of the tsunami hazard data is variable, but commonly comes from state agencies or universities.

If an asset falls within the mapped category 3 storm surge zone, extreme high water zone, or the tsunami hazard zone, it receives an unfavorable score (4) for the extreme event flooding indicator. If it lies outside of these zones, it receives a favorable score (1) for this indicator.

Sea-Level Rise:
The sea-level rise indicator describes the potential rise in water within parks by the year 2050. The data source for this exposure indicator is a NPS-specific sea-level rise inundation model provided by the NPS CCRP. The estimated inundation extent was achieved by utilizing a modified bathtub approach as developed by NOAA, and attempts to account for local and regional tidal variability and hydrological connectivity. Polygon extents consist of 4 model-run scenarios using sea-level change maps produced by Colorado Center for Astrodynamics Research at the University of Colorado in Boulder. The maps are based on Representative Concentration Pathways (RCP), which are four

greenhouse gas concentration trajectories. Two RCPs were modeled, a moderate RCP, 4.5 and the most extreme RCP, 8.5. Each RCP was projected to the years 2050 (condition used for this protocol) and 2100. One caveat of these data is that the model does not incorporate local land level change (subsidence or uplift). For many parks this is not a problem, as this change is relatively small compared to the amount of predicted water level rise. However, the sea-level rise data in parks with high rates of subsidence (parks in southern Louisiana) or uplift (many Alaska parks) will require adjustment.

If an asset falls within the mapped 2050 SLR zone, it receives an unfavorable score (4) for the sea-level rise indicator. If it lies outside of the mapped SLR zone, it receives a favorable score (1).

Shoreline Change:
For most parks, particularly those along the U.S. East and Gulf coasts, shoreline **erosion** buffers are created using known erosion rate data. These data are commonly acquired from the U.S. Geological Survey, Coastal and Marine Geology Program or from state coastal management programs. Short-term erosion rates (usually data ranging from the 1970s to 2004) are utilized to make buffer zones for a 35-year time frame. Rates are binned into the following categories before buffering: 1m/year, 2m/year, 4m/year, 6m/year, 8m/year, etc. (continuing increments of 2 meters).

Many national parks along the west coast of the U.S. contain steep cliff shorelines. In some cases, these shorelines are retreating significantly due to cliff erosion; this is particularly true of areas comprised of unconsolidated materials (sands and gravels) or loosely consolidated bedrock (commonly sedimentary rock). In these cases, cliff retreat data will be utilized in place of erosion rate data (when available). Like erosion rates, the cliff retreat rates are utilized to make **cliff retreat** buffer zones for a 35-year time frame (2050). Below 1 meter, retreat rates are binned into detailed increments, with categories of: 0.25m/year, 0.5m/year, 0.75m/year, and 1m/year, and the same categories as shoreline erosion for rates above 1 meter: 1m/year, 2m/year, 4m/year, 6m/year, 8m/year, etc. (increments of 2 meters).

For shorelines without erosion or cliff retreat rate data (ocean, estuarine, or developed areas), a simple **coastal proximity** buffer is applied. The coastal proximity buffer distance used is 35 meters, which can accommodate an erosion rate up to 1m/year, and can account for the fact that infrastructure close to the shoreline is highly likely to experience a range of coastal hazards within the 35 year (2050) timeframe of this analysis.

If an asset falls within the erosion, cliff retreat, or coastal proximity buffer zone, it receives an unfavorable score (4) for this indicator. If it lies outside of these zones, it receives a favorable score (1).

Reported Coastal Hazards:
All of the other exposure indicators represent the *potential* area that could be affected by coastal hazards; the zones do not represent data from actual past events. Therefore, it is essential to have one indicator that includes actual reported coastal hazards. Understanding what has happened in the past in an area is essential to predicting what may happen in the future.

Historical flooding information for each park is commonly obtained from a questionnaire that is completed by park staff. Historical flooding information is also derived from storm imagery, reconnaissance visits, and direct communication with park personnel. For this indicator, the following question is posed to park personnel as part of the questionnaire:

Have any of the following assets (or lands around the asset) been FLOODED in previous storm events? * This question is referring to the lands or area around an asset. Even if the asset was not built during a particular storm, we would like to know if that location has been flooded in the past.

For high elevation parks with cliff retreat and no flooding hazards, a similar question is asked for this indicator, and is related to **visible slope instability**. For cliff retreat, it is important to know if the landscape around an asset is currently showing signs that further retreat and erosion is imminent.

After scores are given for each exposure indicator (either 1 or 4), they are summed and binned to get a total exposure score for each asset. Final binned exposure scores fall into one of four ranking categories (based on the number of exposure zones): minimal exposure (asset does not lie within any mapped hazard zone), low exposure (1 zone only), moderate exposure (2-3 zones), and high exposure (4-5 zones). Specific scoring ranges can be found within the Excel results sheets. Any assets that obtain an exposure ranking of minimal are not further analyzed for sensitivity. Finally, all asset types (transportation and structures) are analyzed for exposure using the same general methodology.

Step 2: Sensitivity Analysis

The second step in the protocol is to analyze the sensitivity of NPS assets to coastal hazards and sea-level rise. Similar to exposure, a set of indicators was determined for asset sensitivity. Unlike exposure, however, sensitivity is evaluated independent of location (only exposure is location-dependent). Sensitivity refers to how that asset would fare when exposed to the hazard, which is a function of the inherent properties or characteristics of the asset. While the sensitivity indicators for structures and transportation assets are generally the same (Table 6), how sensitivity is addressed during design and construction is very different.

Because digital sensitivity data are not generally available, the primary data source for much of the sensitivity analysis is an asset-specific questionnaire. This questionnaire contains detailed questions related to the various sensitivity indicators (e.g., is the structure elevated above base flood elevation). It is distributed to appropriate personnel within each unit— typically individuals that possess long institutional memory and familiarity with park facilities. Where appropriate, sensitivity data is also obtained from FMSS, the National Bridge Inventory, aerial imagery, and site visits.

Bridges are considered transportation assets, but have additional factors that must be considered when analyzing sensitivity to coastal hazards and sea-level rise. Table 6 summarizes the four general sensitivity indicators (for all assets), as well as the four additional bridge indicators. The following section describes each sensitivity indicator in detail, including data sources, methodology, and scoring.

Table 6. Sensitivity Indicators for Asset Coastal Hazards and Sea-Level Rise Vulnerability Protocol

Sensitivity Indicator	Data Sources
☑ Flood Damage Potential (Elevated)	Asset questionnaire; direct measurements of threshold elevation
☑ Storm Resistance & Condition	Asset questionnaire; FMSS database
☑ Historical Damage	Asset questionnaire; discussion with park staff
☑ Protective Engineering	Asset questionnaire; field & aerial imagery analysis; WCU Engineering Inventory
Additional Bridge Indicators	
☑ Bridge Clearance	National Bridge Inventory (item 39)
☑ Scour Rating	National Bridge Inventory (item 113)
☑ Bridge Condition	National Bridge Inventory (item 59 & 60)
☑ Bridge Age	National Bridge Inventory (item 27); FMSS database

Flood Damage Potential:
The flood damage potential indicator represents how likely an asset is to be inundated if the surrounding land area is flooded. For structures, this usually means whether or not the building is constructed on elevated stilts or pilings. Alternatively, fill be added to the surrounding land to artificially elevate the asset above local ground height. This information is commonly obtained through the park questionnaire or visual inspection during site visits. For this indicator, the following question is posed to park personnel as part of the questionnaire:

Are any of the following assets elevated at least 5 feet above local ground level (including critical utilities)? Examples include: 1) assets on stilts or pilings, or 2) assets built on artificial fill material above local ground level. NOTE: If elevated, but not quite 5 feet, indicate in comments.

When available, threshold elevation data collected by the NPS Resource Information Services Division (RISD) are included in the sensitivity analysis. These data, which have been collected at only a handful of parks thus far, are acquired with sub-centimeter Global Positioning System (GPS) equipment in order to record accurate threshold and asset elevations. In parks that do not have these data, the questionnaire (in combination with field work) is the primary data source used to determine whether an asset is elevated. The questionnaire generally inquires whether an asset is elevated above ground level – in the case of structures, at least 5 feet. Ideally, elevation of an asset would be compared to FEMA's Base Flood Elevation (BFE), and the precise threshold elevations acquired by RISD make this comparison possible. This can aid in the determination of highly reliable elevation indicators for structures within parks. It should be noted however, that elevation is one of several indicators used to calculate the sensitivity of an asset, and availability of precise elevation data, while preferable, is not critical in gauging overall sensitivity and vulnerability.

The precise threshold elevation verifies the first metric (flood damage potential) within the sensitivity analysis. This elevation is compared to local BFE for each asset to determine if the asset's primary threshold was above or below BFE. If an asset is elevated above BFE, it will receive a favorable score for the flood damage potential sensitivity metric (only if it is within a FEMA flood zone).

If an asset is reported to be elevated on stilts, built on elevated fill, or has a threshold above FEMA BFE, it receives a favorable score (1) for the flooding potential indicator. If it is not elevated (built at grade), it receives an unfavorable score (4) for the indicator.

Storm Resistance & Condition:
This sensitivity indicator represents how well an asset will resist damage from coastal hazards based on two factors: 1) overall storm resistance and 2) condition. Assets built to storm-resistant standards, with quality construction, or in good condition are less likely to be damaged by coastal hazards. For this indicator, the following two questions are posed to park personnel:

Are any of the following assets built to resist flood/wave storm damage? Examples include: 1) assets built to specific storm-resistant standards/engineering codes, or 2) assets particularly or inherently resistant to other forms of damage or deterioration (e.g., fortifications).

Are any of the assets listed below particularly vulnerable to flood/wave damage due to condition? In other words, is the asset in poor condition due to deterioration, lack of maintenance, etc.? DO NOT consider the location of the asset (even if it is near the water or commonly flooded), only consider the physical condition of the asset itself. The condition should be considered independent of the asset's location.

This sensitivity indicator is scored as a combination of storm resistance and condition. If an asset is reported to be storm resistant, it receives a favorable score (1) for half of the total score for this indicator (and vice versa). If the asset is reported to be in poor condition, it receives an unfavorable score (4) for half of the total score for this indicator (and vice versa).

Historical Damage:
The historical damage indicator represents if an asset has been damaged by coastal hazards in the past, as assets that have been previously damaged are more likely be damaged in the future. This is similar to the reported coastal hazards exposure indicator, but instead of focusing on the site or area around an asset, this indicator is focused on damage to the asset itself. For this indicator, the following question is posed to park personnel as part of the questionnaire:

Have any of the following assets been significantly DAMAGED in previous storm/flooding events (water/wave damage only)? * This question is focused on the actual damage from an event (the prior flooding question is about the LAND near the asset being inundated)

If an asset is reported to have been damaged in the past, it receives an unfavorable score (4) for this indicator. If it has not been damaged in the past it receives a favorable score (1) for the indicator.

Protective Engineering:
This indicator represents if an asset is protected by engineering including hard structures (e.g., seawalls, bulkheads) or landscape modifications (e.g., significant drainage alteration, major restored landscape). This indicator assumes that assets protected with engineering are less likely to be damaged by coastal hazards. Data sources include the questionnaire, the NPS coastal engineering inventory, and site visits. The following question is posed to park personnel as part of the questionnaire:

Are any of the following assets currently being protected by an engineered structure (e.g., seawall, bulkhead) or other major engineering (e.g. drainage, major landscape modification, major restored landscape)? Explain if needed.

If an asset is reported to be protected by engineering, it receives a favorable score (1) for this indicator; if the asset is not protected by engineering, it receives an unfavorable score (4) for the indicator.

Bridge Indicators: Clearance, Scour Rating, Condition, and Age:
For bridges within the National Bridge Inventory (NBI) database (public bridges over 20 feet in length), additional indicators are considered; the data for these indicators comes directly from the NBI database. The bridge sensitivity additional indicators include: clearance, scour rating, condition, and age. Table 7 below describes each indicator, including the description, rationale, and scoring.

Table 7. Additional Bridge Indicators

Indicator	Description & Rationale	Scoring (NBI score = sensitivity score)
Clearance	Bridges with higher clearance above the water surface are less likely to be damaged by coastal hazards.	*Amount of clearance in feet*: > 15 = 1; 9-15 = 2; 1-8 = 3; 0= 4
Scour Rating	Bridges with scour issues are more likely to be damaged by coastal hazards.	*Rating*: n/a = 1; low & stable (5-8) = 2; stable (4) = 3; critical = 4
Condition	Bridges in poor condition are more likely to be damaged by coastal hazards.	*Condition Rating*: n/a = 1; 0-3 = 2; 4-6 = 3, 7-9 = 4
Age	Bridges closer to their lifespan are more likely to be damaged by coastal hazards.	*Age (in years):* 0-25 = 1; 26-50 = 2; 51-75 = 3; > 75 = 4

To calculate a sensitivity score, each asset is first given a score for all applicable indicators. These scores are summed to obtain a total raw score for sensitivity, then binned into three categories reflective of the number of unfavorable indicators: low sensitivity, moderate sensitivity, and high sensitivity. Specific scoring ranges can be found within the Excel results sheets.

Step 3: Vulnerability Calculation
To obtain a vulnerability score for each asset, the exposure and sensitivity scores are summed, and then binned into four vulnerability ranking categories. The ranking categories are as follows: minimal vulnerability (assets with minimal exposure and not included in the sensitivity analysis), low vulnerability, moderate vulnerability, and high vulnerability. Specific scoring ranges for vulnerability can be found within the Excel results sheets. A subset of the assets from the completed vulnerability analysis will be chosen for development of adaptation strategies (step 4).

Step 4: Adaptation Strategies Analysis
After the vulnerability analysis is complete, adaptation strategies will be analyzed for key assets within each park. FMSS data such as Asset Priority Index (API) and Optimizer Band (OB) can help select the assets to analyze for adaptation strategies. Assets analyzed will likely include those with high vulnerability and high priority and/or high criticality (API/OB), as well as high vulnerability assets with low priority and/or criticality. This adaptation analysis begins with discussions with the park, or by way of a questionnaire. This portion of the analysis focuses on the options available to the park to reduce the overall vulnerability of key assets. An outline of potential adaptation strategies to reduce coastal hazards and sea-level rise vulnerability has been compiled by WCU for both structures and transportation assets (Table 8).

Table 8. Adaptation Strategies to Reduce Vulnerability of Assets to Coastal Hazards and Sea-Level Rise

Adaptation Action	Effect on Vulnerability and Rationale
☑ **Elevate**	Reduces the **sensitivity** of the asset; elevating a structure (and critical utilities) or transportation asset (i.e., a road) reduces the risk of flood damage.
☑ **Relocate**	Reduces the **exposure** of the asset; relocating the asset to a lower risk area reduces the likelihood that it will experience impacts from coastal hazards/SLR.
☑ **Protect/Engineer**	Reduces the **exposure** and/or **sensitivity** of the asset; protecting the asset with an engineered structure or landscape modifications (i.e., drainage) can reduce the likelihood that the asset will experience, or obtain damage from, coastal hazards/SLR.
☑ **Decommission & Remove**	Eliminates the vulnerable asset.
☑ **Storm-Resistant Redesign**	Reduces the **sensitivity** of the asset; redesigning the asset to be more storm resistant can reduce the likelihood of damage from coastal hazards/SLR.
☑ **Engineering Downgrade** (transportation assets only)	Reduces the **sensitivity** of the asset; downgrading the amount of engineering (i.e., replacing paved parking lot with shell material lot) can reduce the cost of rebuilding after damage and gives more flexibility for replacement.

This protocol is designed solely to assess the vulnerability of physical infrastructure. However, there are other adaptation actions for vulnerable assets that would not reduce the vulnerability of the physical asset, but instead its function. For example, a park might consider moving the critical contents within a building to a higher floor to reduce potential flood damage. Similarly, parks may decide to shift an asset's function to a less vulnerable asset. These adaptation actions do not change the vulnerability of the original asset (i.e., exposure and sensitivity remain the same); instead these actions change the criticality of the asset, potentially making it less of a concern to the park.

Additional NPS Climate Change Resources

Additional efforts are being made by NPS to address climate change in the coastal zone, as well as other critical environments. A number of these studies aim to improve the understanding of overall trends in climate change stressors, while others have focused on recording the specific effects of those stressors on natural and cultural resources within parks. Using this research and the latest climate science, the NPS is guiding adaptation efforts at units nationwide. Below are some of the climate change related resources at NPS:

- General Climate Change at NPS: http://www.nps.gov/subjects/climatechange/index.htm
- Climate Change Adaptation for Cultural Resources: http://www.nps.gov/subjects/climatechange/adaptationforculturalresources.htm
- Coastal Adaptation: http://www.nps.gov/subjects/climatechange/coastaladaptation.htm
- NPS Climate Change Adaptation Plan: http://www.nps.gov/orgs/ccrp/upload/NPS_CCActionPlan.pdf