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Park Facility Management Division - Sustainable Operations Branch
Park Facility Management Division - Facilities Planning Branch

Cape Lookout National Seashore

Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment
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Program for the Study of Developed Shorelines
Western Carolina University
Cullowhee, NC 28723

Contents

Executive Summary……3

Vulnerability Assessment Products & Deliverables……4

Digital Data Sources……4

Introduction & Project Description……5

General Protocol Methodology……6

Results Summary & Discussion……7

Exposure Analysis……7

Sensitivity Analysis……9

Threshold Elevation Data Collection ……9

Vulnerability Calculation……11

Unique Factors & Considerations……15

Erosion Rate Data ……15

FEMA Flooding Data……15

Sea-Level Rise Data……15

Sand Roads at CALO……17

Vulnerability Assessment Methodology……18

Step 1: Exposure Analysis & Mapping……18

Step 2: Sensitivity Analysis……21

Step 3: Vulnerability Calculation ……24

Step 4: Adaptation Strategies Analysis……24

Additional NPS Climate Change Resources……25

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Cover Photo: Cape Lookout Lighthouse (Photo credit: Program for the Study of Developed Shorelines at Western Carolina University).

Executive Summary

The National Park Service (NPS), in partnership with Western Carolina University's (WCU) Program for the Study of Developed Shorelines (PSDS), has developed a **Coastal Hazards and Sea-Level Rise Asset Vulnerability Assessment Protocol**. This protocol is meant to assess the vulnerability of infrastructure to multiple coastal hazards and climate change factors (i.e., erosion, flooding, storm surge, sea-level rise, and historical flooding), over a 35-year planning horizon (2050). Unlike natural resource vulnerability, which combines three metrics (exposure, sensitivity, and adaptive capacity), the newly developed method for assessing infrastructure includes only exposure and sensitivity to coastal hazards and climate change factors in the vulnerability score; adaptation strategies are instead examined in the context of the vulnerability results. 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.

A total of 152 structures (buildings and shelters) and 70 transportation assets (roads, road segments, parking lots, boardwalks, waterfront systems/waterways/marinas, fuel systems, and primary trails) are included in the vulnerability assessment of Cape Lookout National Seashore (CALO). The notable result of the **exposure** analysis at CALO is that 94% of all assets (both structures and transportation) have either high exposure (49%) or moderate exposure (45%) to coastal hazards and sea-level rise. The results also show that the majority of assets have moderate or high **sensitivity.**

Over two-thirds (67%) of all assets analyzed at CALO have high **vulnerability** to coastal hazards and sea-level rise, and another quarter (26%) have moderate vulnerability. In general, a higher percentage of transportation assets are highly vulnerable when compared to structures.

The high vulnerability assets at CALO have a combined current replacement value (within the NPS asset management database) of approximately $42.5 million, which is roughly 35% of the total value of all assets analyzed within the park. The ten most valuable transportation assets all have high vulnerability, including the marinas/waterways at Harkers Island, South Core Banks/Coast Guard area, and the Cape Lookout Historic District. Six of the ten most valuable structures have high vulnerability (including the Cape Lookout Light Station Keeper's Quarters and the Portsmouth Life-Saving Station), and two have moderate vulnerability, including the park's two most valuable assets: the Cape Lookout Lighthouse and Harkers Island Administration Building/Visitor Center.

One structure has both high vulnerability and high priority to the park (asset priority index within the NPS database > 70): the Cape Lookout Light Station Keeper's Quarters. Two structures, the Cape Lookout Lighthouse and Harkers Island Administration Building/Visitor Center, have moderate vulnerability and high priority to the park. All of the high priority transportation assets have high vulnerability, including most segments of the sand roads at North Core Banks, Cape Lookout Historic District, and South Core Banks.

Vulnerability Assessment Products & Deliverables

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

2. Geographic Information Systems (GIS) Maps and Layers – All GIS data, including the exposure layers, exposure results, and final vulnerability results will be sent 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 (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's National Flood Hazard Layer (Official) on ArcGIS.com. All areas of the park are covered by the official National Flood Hazard Layer, although some errors exist (see the Unique Factors & Considerations section for more information). Two primary FEMA flood zones are utilized: the VE and AE zones. 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) - Data provided by NPS CCRP; full publication related to product in press (not accessible yet); metadata is available. Provided to WCU as geodatabase by CCRP. Utilized the KHWK_slr_85_2050 layer, which represents the 2050 sea-level rise inundation model (high scenario). All areas of the park are covered by this sea-level rise layer, although some errors exists (see the Unique Factors & Considerations section for more information).

3. Surge (SLOSH) – Climate Change Response Program (CCRP) - Data provided by NPS CCRP; full publication related to product in press (not accessible yet); metadata is available. Provided to WCU as geodatabase by CCRP. Utilized the C3M_km3, which represents the category 3 mean tide surge model. Was further edited by WCU to show just area of inundation. All areas of the park are covered by the SLOSH model.

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 was applied. The erosion rate buffers and the proximity buffers combined comprise this exposure indicator zone for CALO. Digitized shoreline using ESRI streaming layer at scale of 1:2500.

Introduction & Project Description

The National Park Service (NPS), in partnership with Western Carolina University's (WCU) Program for the Study of Developed Shorelines (PSDS), has 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 and transportation assets in the NPS asset database (Facilities Management Software System; FMSS), but it could be adapted to other resources.

A proposed standardized approach to assessing climate change vulnerability was described in a multiple agency (NOAA, NPS, USGS, DOD, NWF, and USFS) 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 changes in sea level 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 new modified formula for the vulnerability of the built environment (buildings, transportation assets, etc.) is as follows:

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 Vulnerability Assessment Protocol** has four primary steps: 1) Exposure Analysis and Mapping, 2) Sensitivity Analysis, 3) Vulnerability Calculation, 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 climate change exposure (to the year 2050). The exposure analysis utilizes 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., the storm surge 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. CALO specific hazards and data sources for the exposure indicators.

Exposure Indicators	CALO Specific Hazards	CALO Data Sources
Flooding Potential	1% annual flood ± velocity/waves	FEMA Flood Zones (VE or AE)
Extreme Event Flooding	Storm surge	NPS-specific SLOSH model
Sea-Level Rise Inundation	2050 sea-level rise	NPS-specific SLR modeling
Shoreline Change	Erosion & coastal proximity	NC erosion rates & shoreline proximity buffers
Reported Coastal Hazards	Historical flooding	Park questionnaire; storm imagery

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 and 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. Assets with minimal exposure are excluded from the sensitivity analysis, since an asset must be exposed to a hazard in order to be sensitive to it.

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

Unique Factors: Each park has a unique set of conditions based on the data available and the geologic setting. At CALO, the primary unique factors are 1) poorly mapped FEMA data in certain areas of the park, 2) minor errors in the sea-level rise model results near Portsmouth Village, and 3) the division of the sand roads into segments (listed in FMSS as only three roads, split into multiple segments for easier analysis). A more detailed description of these factors, including how they affected the results for CALO, are presented later in the report, in the section titled: Unique Factors & Considerations.

Results Summary & Discussion

A total of **152 structures** (buildings and shelters) and **70 transportation assets** (roads, road segments, parking lots, bridges, boardwalks, waterfront systems/waterways/marinas, fuel system foundations, and primary trails) were included in the vulnerability assessment of CALO. The term "asset" will be used in this document to represent any structure or transportation infrastructure listed in FMSS, regardless of ownership. Also, the results for this vulnerability assessment represent a time frame of approximately 35 years, to the year 2050.

Exposure Analysis

The notable result of the exposure analysis at CALO is that 94% of all assets (both structures and transportation) have either a high exposure (49%) or moderate exposure (45%) to coastal hazards and sea-level rise (Table 2). Among structures, 43% have high exposure, while 50% have moderate exposure. The high exposure structures are concentrated in barrier island districts (Figure 1B), Portsmouth Village (Figure 1C), Long Point and Great Island, as well as Shackleford Banks. Nearly two-thirds (61%) of transportation assets have high exposure, while over one-third (36%) have moderate exposure. The majority of high exposure transportation assets are sand roads (see further discussion in Unique Factors & Considerations section of this document) and bridges that serve the various park districts on North and South Core Banks, as well as dock and marina assets, which are inherently exposed due to proximity to the ocean. However, a few key parking lots at Harkers Island (Visitor Center and Picnic Area) also have high exposure (Figure 1A).

Very few assets (6%) at CALO have low exposure to coastal hazards and sea-level rise (Table 2). Most of the low exposure structures are located at Harkers Island (Figure 1A; Housing Quarters 101, 105, 106; Fire Cache; Radio Shack; RM and Ranger Garages; Maintenance Building). Of all the structures on the barrier islands, only the Coast Guard Station and its Summer Kitchen near Cape Lookout Village have low exposure. Only two transportation assets at CALO have low exposure, both of which are located on Harkers Island (Figure 1A; Maintenance Parking Lot and the unpaved portion of Cape Point Road).

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

Assets	High Exposure		Moderate Exposure		Low Exposure		Minimal Exposure		Total #
	#	%	#	%	#	%	#	%	
Structures	65	43%	76	50%	11	7%	0	0%	152
Transportation	43	61%	25	36%	2	3%	0	0%	70
All CALO Assets	**108**	**49%**	**101**	**45%**	**13**	**6%**	**0**	**0%**	**222**

The overall high exposure scores for CALO are primarily due to the fact that most of the park assets are situated on low-lying barrier islands (Shackleford and Core Banks), and are often in close proximity to the ocean. This places many assets within the storm surge and FEMA flood zones, and has caused many assets to have been flooded in the past. Only the assets situated further inland have moderate or low exposure (Figure 1).

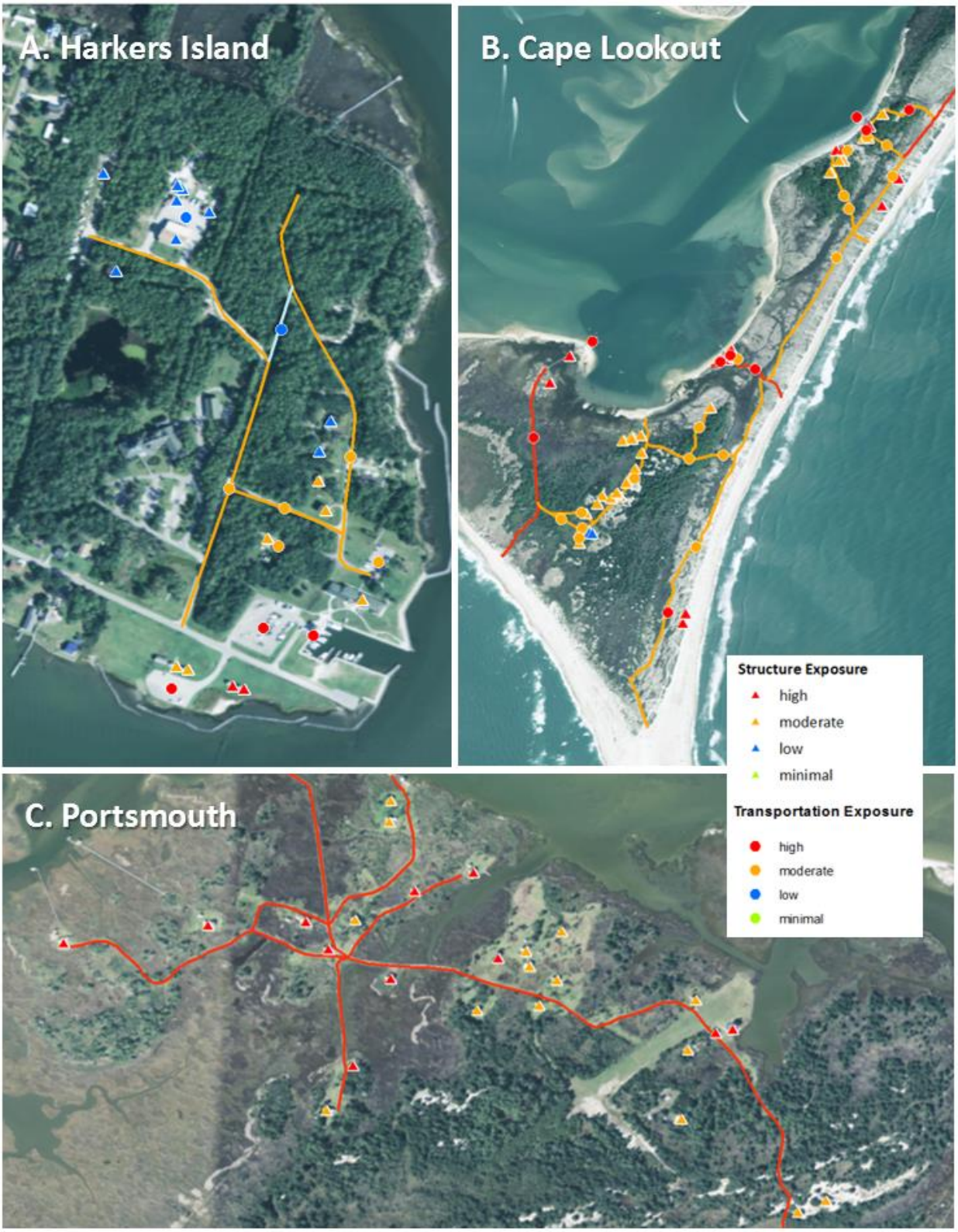

Figure 1. Example of exposure results at CALO. Red indicates high exposure, orange indicates moderate exposure, and blue indicates low exposure at A) Harkers Island, B) Cape Lookout, and C) Portsmouth Village.

Sensitivity Analysis

The sensitivity results for CALO assets (structures and transportation combined) show the majority have either moderate (53%) or high (45%) sensitivity to coastal hazards and sea-level rise (Table 3). When separated into structures and transportation, the scores are slightly different. Most structures have moderate sensitivity (70%), while the transportation assets are primarily high sensitivity (83%). Only 2% of assets have low sensitivity. No assets have minimal exposure (all assets are in at least one exposure zone; Tables 1 and 2); therefore, all assets at CALO were analyzed for sensitivity.

Table 3. CALO 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	42	28%	106	70%	4	3%	152	0
Transportation	58	83%	11	16%	1	1%	70	0
All CALO Assets	**100**	**45%**	**117**	**53%**	**5**	**2%**	**222**	0

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

Of the 153 structures analyzed at CALO, only the Harkers Island Maintenance Building, Cape Lookout Lighthouse and Oil House, and the Summer Kitchen Cistern at Cape Coast Guard Station were reported to be storm resistant. Around one-quarter of structures were reported to be in poor condition, mostly within the Portsmouth Village and Cape Lookout Village areas of the park. In addition, approximately one-quarter of structures were reported to have been historically damaged by coastal storms and flooding. Finally, most structures at CALO are not protected by an engineering structure.

Only one transportation asset at CALO was reported as being elevated: the Fuel System Foundation at Cape Coast Guard Station. Three transportation assets were reported as storm resistant: the Harkers Island Marina, and the Fuel System Foundations at both the Yeoman House and Cape Coast Guard Station. Almost one-third of transportation assets were reported to be in poor condition, and three-quarters were reported to have been historically damaged by coastal storms and flooding. Twelve transportation assets are protected by an engineering structure, most of which are located on Harkers Island.

Threshold Elevation Data Collection

Threshold elevation data collected by the NPS Resource Information Services Division (RISD) 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 elevations acquired by RISD make this comparison possible. This aided in the determination of more reliable sensitivity indicators for assets at CALO.

The precise threshold elevation verifies the first indicator (flood damage potential) of the sensitivity analysis. This elevation was compared to local BFE for each asset to determine if the asset's primary threshold was above or below BFE. In general, if an asset is above BFE and also elevated by design, it received a favorable score for the flood damage potential sensitivity metric. More specific methodology for verifying and using these data can be found in the Vulnerability Assessment Methodology section of this document.

Threshold elevation data was used to verify the first sensitivity metric (flood damage potential) for 98 of the 152 structures analyzed at CALO (data was not used for transportation assets). Sixty-two (63%) of the structures analyzed have threshold elevations above local BFE. This comparative analysis led to revised scores for the elevation metric (as compared to the original questionnaire) for 21 structures. This included one structure that was originally reported as "elevated," which was changed to ***not elevated*** (Casablanca House), and 20 structures originally reported as "not elevated" that were changed to ***elevated*** (e.g., Great Island Cabins 1, 9, 10, and 12; Les & Sally's Main Building; Cape Lookout Light Station Keeper's Quarters and Oil House; Portsmouth Village Equipment Building). Figure 2 illustrates two examples of the threshold elevation verification.

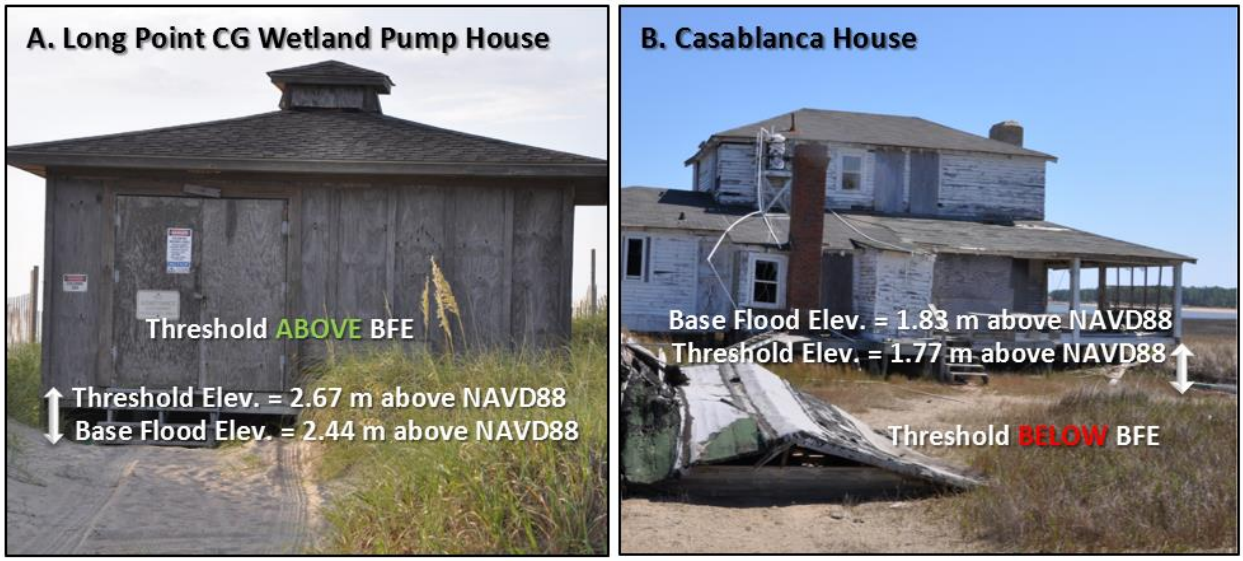

Figure 2. Two CALO structures that had revised scores for the flood damage potential (elevated) sensitivity indicator based on the precise threshold elevation data (collected by NPS-RISD) and BFE values. A) Long Point Campground Wetland Pumphouse was originally reported as not elevated within the questionnaire, but the threshold elevation data showed that the first floor was, in fact, ***above*** BFE. Therefore, this structure was modified to receive a favorable score for the flood damage potential sensitivity indicator. B) Casablanca House was originally reported as elevated within the questionnaire, but the threshold elevation data showed that the first floor was, in fact, slightly ***below*** BFE. Therefore, this structure was modified to receive an unfavorable score for the flood damage potential sensitivity indicator.

Vulnerability Calculation

The majority of CALO assets are either high or moderate vulnerability to coastal hazards and sea-level rise (Table 4, Figures 3 and 4). Over two-thirds (67%) of assets at CALO are high vulnerability, while 26% have moderate vulnerability, and only 7% have low vulnerability. A higher percentage of transportation assets are highly vulnerable compared to structures (87% compared to 58%). There are no assets at CALO with minimal vulnerability.

The high vulnerability assets at CALO have a combined current replacement value (CRV within FMSS) of approximately $42.5 million, which is about 35% of the total CRV of all assets analyzed. When separated into structures and transportation, the statistics are quite different; high vulnerability assets account for 93% of the total CRV for transportation assets, while only 21% of the total CRV for structures are high vulnerability.

The ten most valuable transportation assets all have high vulnerability, including the marinas/waterways at Harkers Island, South Core Banks/Coast Guard area, and the Cape Lookout Historic District. Six of the ten most valuable structures have high vulnerability (including the Cape Lookout Light Station Keeper's Quarters and the Portsmouth Life-Saving Station), and two have moderate vulnerability, including the two most valuable assets, the Cape Lookout Lighthouse, and Harkers Island Administration Building/Visitor Center.

Only one structure has both high vulnerability and high priority to the park (asset priority index [API] > 70; in FMSS): the Cape Lookout Light Station Keeper's Quarters. Two structures, the Cape Lookout Lighthouse and Harkers Island Administration Building/Visitor Center, have moderate vulnerability and high priority to the park. All high priority (API > 70) transportation assets have high vulnerability, including multiple segments of the sand roads at North Core Banks, the Cape Lookout Historic District, and South Core Banks, and the marinas/waterways at the Cape Lookout Historic District, Harkers Island, South Core Banks, and Shackleford Banks.

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

Assets	High Vulnerability		Moderate Vulnerability		Low Vulnerability		Minimal Vulnerability		Total #
	#	%	#	%	#	%	#	%	
Structures	88	58%	51	34%	13	9%	0	0%	152
Transportation	61	87%	6	9%	3	4%	0	0%	70
All CALO Assets	**149**	**67%**	**57**	**26%**	**16**	**7%**	**0**	**0%**	**222**

Figure 3. Vulnerability results for select areas of CALO: 1) Lookout Village, 2) Lighthouse, and 3) Harkers Island. Only select assets are labeled. Background is aerial imagery from the ESRI streaming layer.

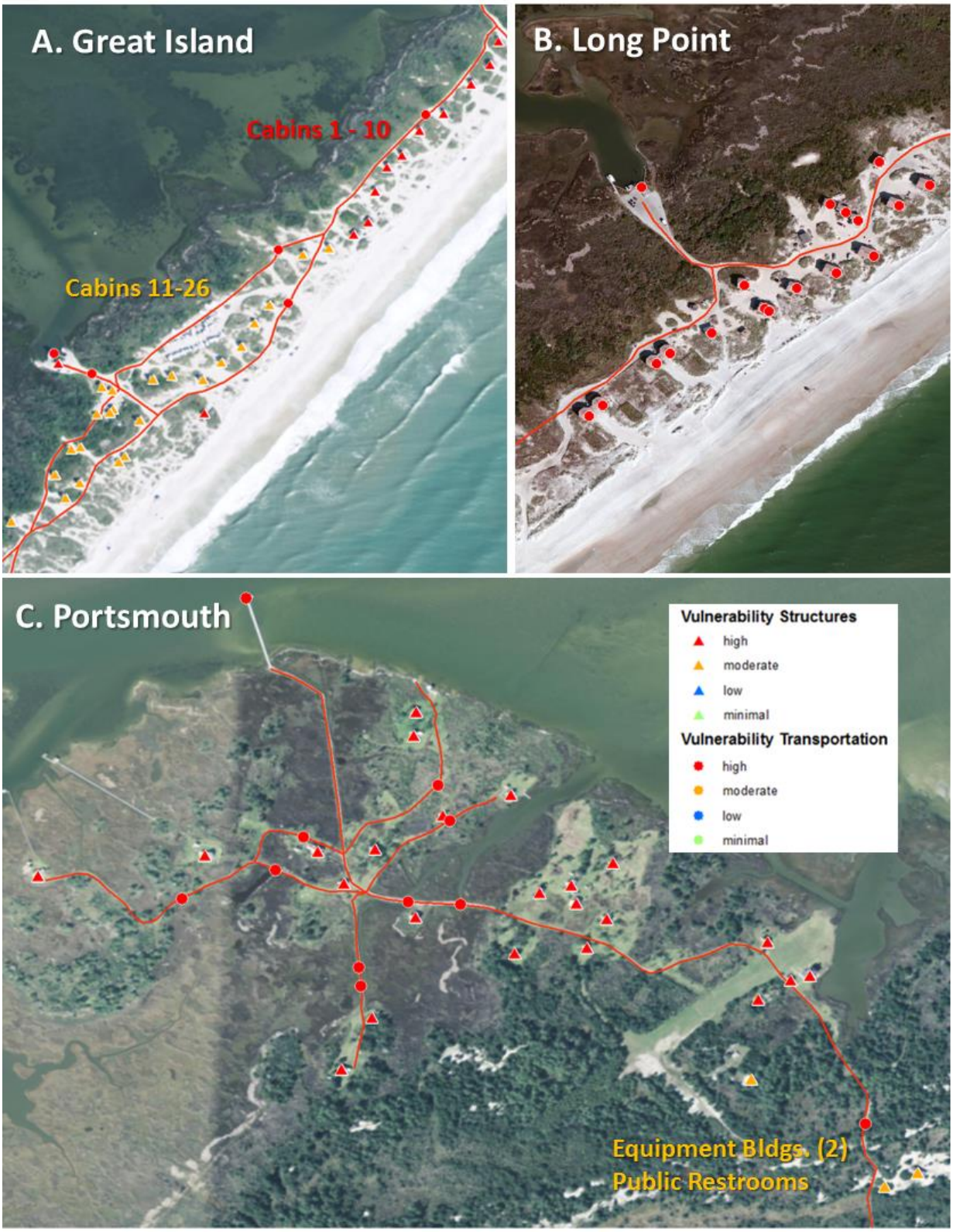

Figure 4. Vulnerability results for select areas of CALO: 1) Great Island, 2) Long Point, and 3) Portsmouth Village. Only select assets are labeled. Background is aerial imagery from the ESRI streaming layer.

Overall, two-thirds (67%) of all CALO assets have high vulnerability using this methodology (Table 4). However, there are several important caveats to the vulnerability assessment and results:

1) This methodology is meant to assess the vulnerability of a park to coastal hazards and climate change factors combined (i.e., erosion, flooding, storm surge, sea-level rise, and historical flooding; see indicator list in Vulnerability Assessment Methodology section). Therefore, a park or section of park (e.g. Portsmouth Village) that has maximum exposure to one or more of these factors (i.e., surge, FEMA VE/AE zones) will inherently have a higher overall exposure, and thus, vulnerability. At the same time, some of the assets at CALO were given a low vulnerability to the analyzed coastal hazards and sea-level rise. This does not mean that these assets will not be affected by one, or more, of these hazards before the year 2050 (the time frame of this study), but instead, that the asset is not within the mapped hazard layers utilized (Table 1). **It is important to note that any coastal asset, especially on a barrier island, could be completely destroyed by a hurricane within any given year.**

2) A major goal of this methodology is to create a standard protocol for vulnerability assessments, regardless of the data utilized. 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, incorporating the more precise data, and increasing the reliability of the vulnerability results (for example, see FEMA Flooding Data, next section).

3) Vehicle access to the assets and ferry dock at Harkers Island depends on several transportation corridors that are not owned by NPS (e.g., Harkers Island Road and bridge, Island Road). 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, landowners, and partners.

4) Because the sand roads at CALO were split into segments for scoring, the actual number (and associated percentages) of assets with a high vulnerability may be lower than reported (all sand roads ended up with a high vulnerability). The sand roads make up only three entries in FMSS (North Core Banks Sand Roads, South Core Banks Sand Roads, and Cape Lookout Historic District Sand Roads), but this study split the sand roads into 40 different segments. The segmentation of the roads can have the effect of skewing the transportation statistics, by giving the appearance of more "roads" than are actually listed in FMSS. A further discussion of this can be found in the Unique Factors & Consideration section of this document.

Unique Factors & Considerations

Erosion Rate Data

Erosion rate data were acquired from North Carolina's Division of Coastal Management. Where available, erosion 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, and then increments of 2 meters/year. For shorelines without erosion rate data (ocean or estuarine) a simple coastal proximity buffer was applied. The erosion rate buffers and the proximity buffers combined comprise this exposure indicator zone for CALO.

FEMA Flooding Data

The FEMA VE Zone for CALO is not well mapped near Cape Lookout (Figure 5), while the AE zone is fairly well mapped. For the areas where the VE zone was missing or incomplete, it was assumed that assets seaward of the AE zone, were in fact located in the VE zone (see yellow arrows in Figure 5).

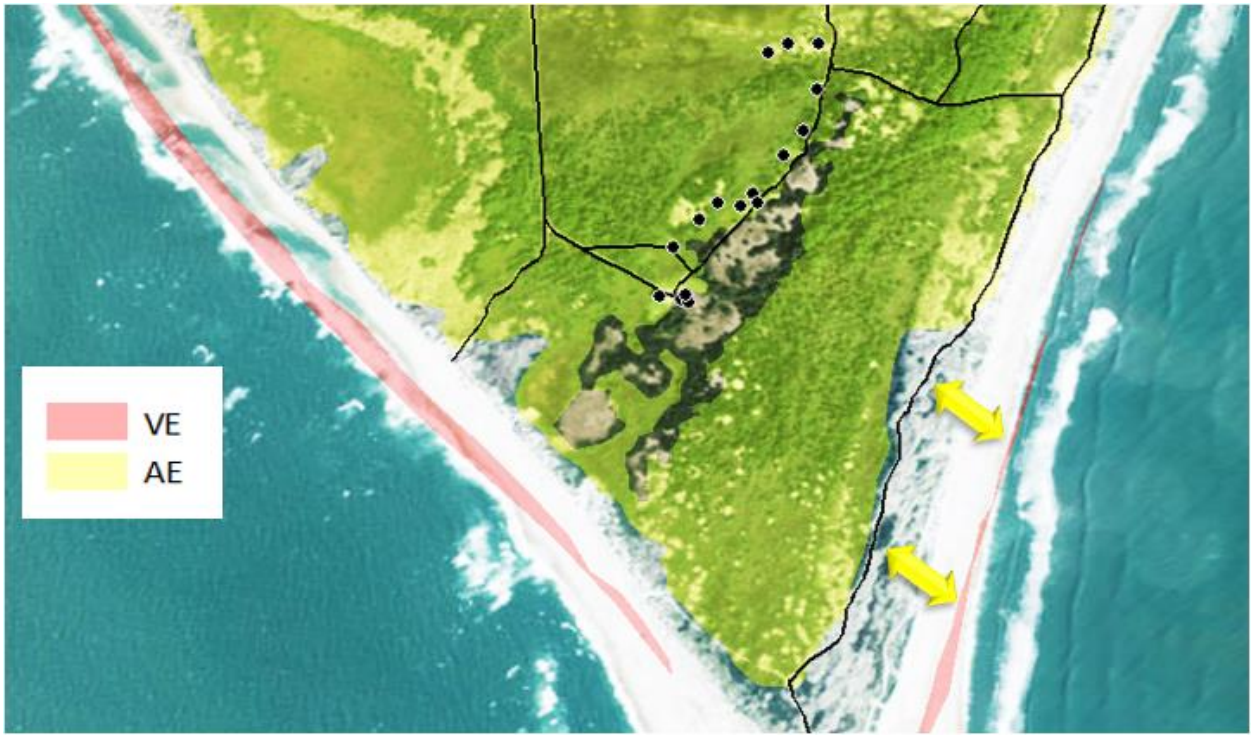

Figure 5. FEMA AE zone (yellow shaded) and VE zone (red shaded) near the Cape Lookout Historic District portion of the park. Notice the limited extent of the VE zone along the beach. Assets seaward of the AE (near yellow arrows) were included in the VE. Background is aerial imagery from the ESRI streaming layer.

Sea-Level Rise Data

The 2050 sea-level rise model data had a minor issue in the Portsmouth Village district of CALO. The course grid cell size used to produce the sea-level rise model left an artificial boundary that cut across the topographic grain of the island (Figure 6). Therefore, the sea-level rise data was compared to the LiDAR Digital Elevation (DEM) model data at Portsmouth Village and was used to "ground truth" the sea-level rise inundation model in places where the two datasets were in disagreement.

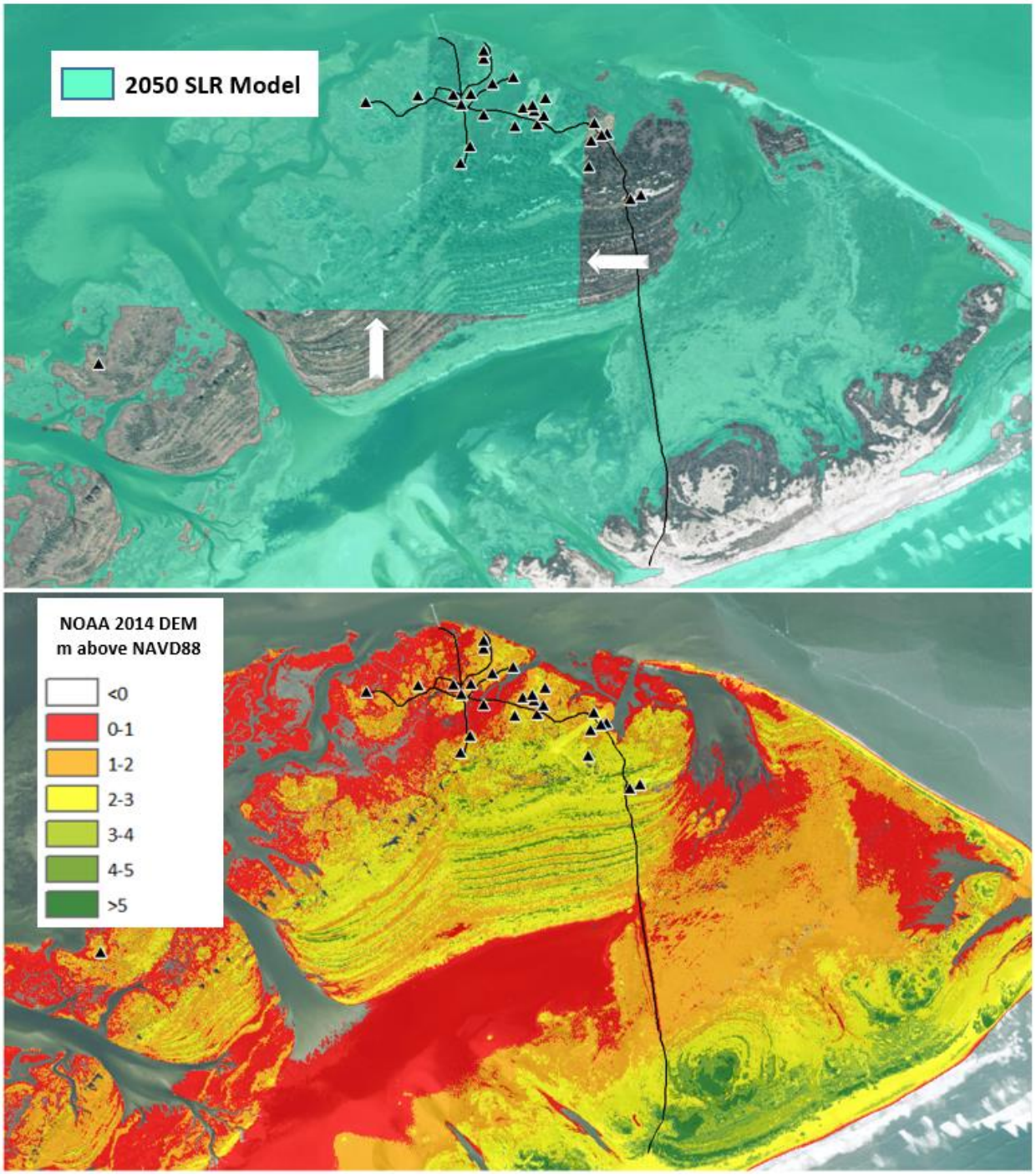

Figure 6. Sea-level rise data errors in the Portsmouth area of the park. For both images, black triangles = structures and black lines = sand roads. Background is aerial imagery from the ESRI streaming layer. **Top:** Sea-level rise model results for CALO (blue/green shade = mapped area of inundation for the 2050 sea-level rise model). Notice the artificial boundaries of the mapped zone running across the topography (beach ridges) almost perfectly east-west and north-south in the central portion of the image (see white arrows). **Bottom:** Digital elevation model utilized for comparison and verification against the sea-level rise model results (above). Notice the areas with the artificial boundaries (just south of the structures) in the sea-level rise data from the top image correlate to continuous beach ridges/dunes.

Sand Roads at CALO

There are no paved roads on the barrier island portions of CALO; all the roads that serve the various assets are sand roads. These roads are often long and linear, continuing for miles, intersecting with numerous other sand roads along the way. Furthermore, in FMSS, over 40 miles of sand roads on the barrier islands are listed as just three assets (North Core Banks Sand Road, South Core Banks Sand Road, and Cape Lookout Historic District Sand Road). For example, all the various roads and spurs at Cape Lookout Village (Figure 7) are listed in FMSS simply as Cape Lookout Historic District Sand Road.

In order to acquire exposure and sensitivity data for the roads at CALO, the sand roads in the barrier islands were divided into segments (North Core, 14 segments; South Core, 12 segments; and Cape Lookout, 14 segments). These segments were based on several factors, primarily exposure level and connectivity/access to other park assets. The segmentation of the roads can have the effect of skewing the transportation statistics by giving the appearance of more roads than are actually listed in FMSS.

In the exposure analysis, 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 intersects in the middle of the road).

Figure 7. Example of segmented sand roads at CALO. Large image: Segments of the sand road in the Historic Cape Lookout Village area of the park; these segments are listed as only one asset within FMSS. Inset: Example of a sand road at CALO.

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