National Park Service
U.S. Department of the Interior

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

Colonial National Historical Park (COLO)

Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment
February 2017

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

Contents

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Please cite this report as: Peek, K.; B. Tormey; H. Thompson; R. Young; S. Norton; J. McNamee; R. Scavo. February 2017. Colonial National Historical Park Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment. NPS 333/154061. National Park Service, Washington DC.

Cover Photo Credit: Photo from Colonial National Historical Park; Program for the Study of Developed Shorelines at Western Carolina University.

NPS 333/154061, February 2017

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., flooding potential, extreme event flooding, shoreline change, sea-level rise, and reported costal hazards), 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 of this protocol 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 77 structures (buildings and fortifications) and 125 transportation assets (roads, road segments, parking lots, bridges, culverts, tunnels, fueling systems, shorelines, and boardwalks) are included in the vulnerability assessment of Colonial National Historical Park (COLO). Vulnerability results show almost equal percentages of assets with high, moderate, and low vulnerability rankings (between 11% and 13%), and the majority (63%) of assets at the park are minimal vulnerability. The only structures with high vulnerability are the Glasshouse Factory and Factory Ruins Shelter in the Jamestown area, and the Archer Cottage and Cottage Outbuilding in the Yorktown area. Moderate and high vulnerability structures at COLO have a current replacement value (within the NPS asset management database) of almost $13 million. Forty transportation assets have either moderate or high vulnerability, and have a combined replacement value of $351 million.

The majority (63%) of all assets at COLO have minimal exposure to coastal hazards and sea-level rise, while only 14% are high exposure. The large number of minimal exposure assets can be attributed to the widespread geographic nature of the park. Most of the minimal exposure assets in the park are located within the higher elevation Yorktown and Central (Williamsburg) areas of COLO, while most of the high exposure assets are within the Jamestown area of the park, which has significantly lower elevations and a history of coastal flooding. The sensitivity results for COLO show that the majority of assets analyzed (excluding those with minimal exposure) have moderate sensitivity. Threshold elevation data collected by the NPS Resource Information Services Division were also included in the sensitivity analysis; these data helped verify the flood damage potential metric within the sensitivity analysis.

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. Federal Emergency Management Agency (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. 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 COLO_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.

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 - Simple shoreline buffer of 35 meters. 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 up 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 zone (e.g., the storm surge zone) are assigned a higher score than assets 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 (does not lie within any mapped zone), low exposure (1 zone), moderate exposure (2-3 zones), and high exposure (4-5 zones).

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

Exposure Indicator	COLO Specific Hazard	COLO Data Source
Flooding Potential	1% annual flood ± velocity/waves	FEMA Flood Zones (VE or AE, see page 14)
Extreme Event Flooding	Storm surge	NPS-specific SLOSH[1] model, Cat 3
Sea-Level Rise Inundation	2050 sea-level rise	NPS-specific SLR modeling
Shoreline Change	Erosion & coastal proximity	Shoreline proximity buffers
Reported Coastal Hazards	Historical flooding	Park questionnaire; storm imagery

[1]Sea, Lake, and Overland Surges from Hurricanes

Sensitivity Analysis: Sensitivity is a function of the inherent properties or characteristics of an asset. A set of primary indicators has also been determined for asset sensitivity: flood damage potential, storm resistance and condition of the asset, historical damage to the asset, 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 Analysis: 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 outside the mapped hazard zones), low, moderate, and high.

Unique Factors: Each park has a unique set of conditions based on the data available and the geologic setting. At COLO, the primary unique factors are: 1) the use of precise threshold elevation data to verify the flood damage potential indicator, and 2) the segmentation of the Colonial Parkway into 15 segments for analysis. A more detailed description of these factors, including how they affected the results for COLO, are presented later in the report, in the section titled: Unique Factors & Considerations.

Results Summary & Discussion

A total of **77 structures** (buildings and fortifications) and **125 transportation assets** (roads, road segments, parking lots, bridges, culverts, tunnels, fueling systems, shorelines, and boardwalks) were included in the vulnerability assessment of COLO. 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, up to the year 2050. This document provides a general summary of the results for exposure, sensitivity, and vulnerability of structure and transportation assets at COLO. 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 Analysis:

The majority of all assets at COLO have minimal exposure to coastal hazards and sea-level rise (66%), while only 14% are high exposure (Table 2). Minimal exposure within this protocol means that the asset did not fall within **any** of the mapped exposure hazard zones (flooding, storm surge, erosion, sea-level rise, and historical flooding- see Methodology section at end of document). The large number of limited exposure assets can be attributed to the widespread geographic nature of the park. The primary portion of the park stretches across Virginia from Jamestown north over 20 miles to Yorktown, encompassing a wide variety of elevations and environments (both coastal and upland). Most of the minimal exposure assets in the park are located within the higher elevation Yorktown and Central (Williamsburg) areas of COLO (Figure 1).

Most of the high exposure assets at COLO are within the Jamestown area of the park, which has significantly lower elevations and a history of coastal flooding (Figure 1). In addition, eleven assets in the Yorktown area of the park have high exposure, most of which are transportation assets (bridges, parking lots, and road segments) located directly adjacent to the York River. In fact, transportation assets make up most of the high exposure assets at COLO; only three structures in the whole park are highly exposed (Glasshouse Factors Ruins Shelter, Archer Cottage, and Archer Cottage Outbuilding).

Numerous areas and assets (44) at COLO were reported to have been flooded in the past. This flooding was primarily from storm surge generated by Hurricane Isabel in 2003. Flooding was particularly high along the James River, affecting several assets in the Jamestown area of the park. This included the Visitor Center, which had to be completely rebuilt after the storm.

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

Assets	High Exposure		Moderate Exposure		Low Exposure		Minimal Exposure		Total #
	#	%	#	%	#	%	#	%	
Structures	3	4%	6	8%	5	6%	63	82%	77
Transportation	26	21%	19	15%	15	12%	65	52%	125
All COLO Assets	**29**	**14%**	**25**	**12%**	**20**	**10%**	**133**	**66%**	**202**

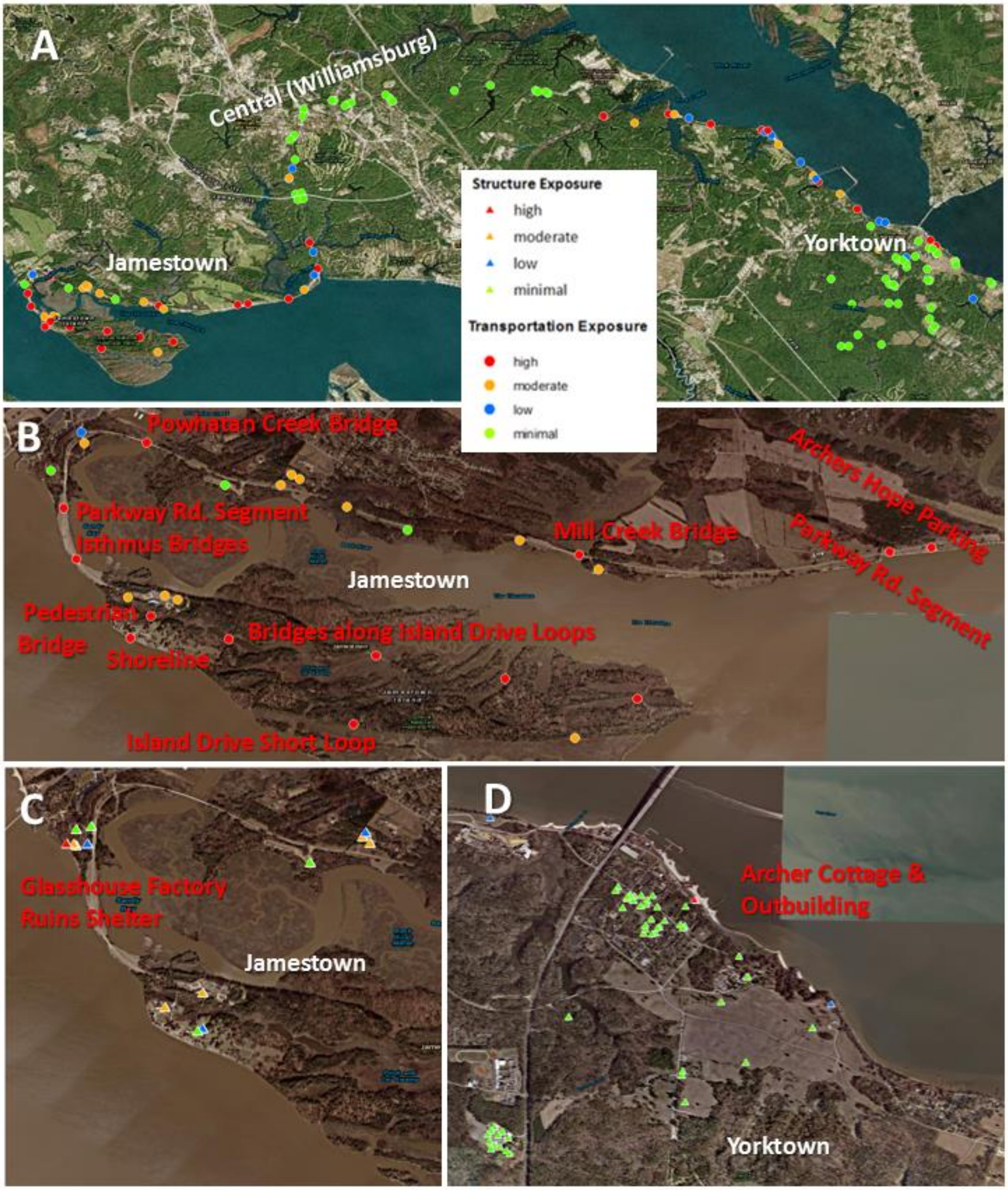

Figure 1. Example of the exposure results for COLO. A) Exposure results for all transportation assets at COLO, highlighting the three primary areas of the park: Jamestown, Central (Williamsburg), and Yorktown. B) Exposure results for transportation assets in the Jamestown area of the park. C) Exposure results for structures in the Jamestown area of the park. D) Exposure results for structures in the Yorktown area of the park. Background is aerial imagery from the ESRI streaming layer.

<u>Sensitivity Analysis:</u>
The sensitivity results for COLO show that the majority of assets analyzed (excluding those with minimal exposure) have moderate sensitivity (Table 3). The results for each individual sensitivity indicator vary, but the majority of moderate sensitivity assets have unfavorable scores (4) for protective engineering and storm resistance, and favorable scores (1) for flood damage potential and historical damage. This trend is particularly true for transportation assets; the results for structures are slightly different. Most structures have unfavorable scores (4) for flood damage potential and storm resistance, and favorable scores (1) for condition.

Only two structures have a high sensitivity, the Glasshouse Factory and the Yorktown Beach Comfort Station. These two structures have unfavorable scores for all indicators with the exception of condition. Six transportation-related assets have a high sensitivity, four of which are shorelines in the park (York River, James River, Jamestown Island, and Swans Point), and two are roads (Colonial Parkway from Indian Field Creek Bridge to Yorktown River Parking and Jamestown Access Road).

Threshold Elevation Data Collection at COLO
Threshold elevation data collected by the NPS Resource Information Services Division (RISD) were also 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 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 aided in the determination of highly reliable elevation indicators for a few structures at COLO. 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 was compared to local BFE for each structure (if data was collected) to determine if the structure's primary threshold was above or below BFE (Figure 2). If an asset was elevated above BFE, it received a favorable score (1) for the flood damage potential sensitivity metric. This comparative analysis led to revised elevation metrics for several assets, including the Glasshouse Factory and Factory Ruins Shelter, Jamestown Historic Research Center, and the Archer Cottage Building. All of these assets except the Historic Research Center were originally reported as being elevated 5 feet above ground level, but the elevation data collection showed thresholds below BFE. Therefore, the scores for the flood damage potential indicator were changed from favorable (1) to unfavorable (4). The opposite was true for the Research Center, which was not reported as being elevated 5 feet above local ground level, but had a threshold elevation above BFE (Figure 2). In this case, the score was changed from unfavorable (4) to favorable (1).

Table 3. COLO 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	2	14%	12	86%	0	0%	14	63
Transportation	6	10%	36	60%	18	30%	60	65
All COLO Assets	**8**	**11%**	**48**	**65%**	**18**	**24%**	**74**	128

*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.

Location	Flood Damage Potential (Elevated) (Q2)	BFE (m, NAVD88)	Threshold Elev (m, NAVD88)	Threshold Above or Below BFE
*Glasshouse Factory 42J630A4	4	2.44	1.733	*Below
Jamestown Maintenance Office /Eq Storage 42J510T3	4			
Jamestown Maintenance Fire Cache/Storage 42J512T4	4			
*Glasshouse Factory Ruins Shelter 42J630M4	4	2.44	1.480	*Below
Jamestown Visitor Center 42J590A5	4			
Glasshouse Factory Support Building 42J630Z5	4			
Glasshouse Storage Bldg 42J630P4	1	2.44	4.360	Above
*Jamestown Historic Research Cntr 42J570A5	1	2.13	2.885	*Above
Jamestown Virtual Viewer 42J592M5	1			
Yorktown Beach Comfort Station 42Y300D4	4			
*Archer Cottage Outbuilding 41Y252K4	4	2.44	2.335	*Below
Redoubts 9 & 10 Fortifications	4			
Fusilers & French Trench Fortifications	4			
Archer Cottage 41Y252A1	1	2.44	2.807	Above

Figure 2. Snapshot of sensitivity results for structures at COLO, including the flood damage potential metric and threshold elevation comparative analysis (no data was collected for structures with empty cells). The flood damage potential metric scores were modified based on the threshold elevation data for structures with an asterisk.

Vulnerability Calculation:

Results from COLO yielded almost equal percentages of assets with high, moderate, and low vulnerability rankings (between 11 and 13%, Table 4, Figure 3). However, the majority of assets at the park are minimal vulnerability (63%). This does not mean they are not vulnerable to any coastal hazards, but that these assets are not within any of the exposure zones analyzed as part of this study. Only 23 assets at COLO have a high vulnerability, 19 of which are transportation assets (Figure 3). Of these 19 high exposure transportation assets, seven are roads (or road segments), three are parking lots, five are bridges, and four are shorelines. The only structures with high vulnerability are the Glasshouse Factory and Factory Ruins Shelter in the Jamestown area, and the Archer Cottage and Cottage Outbuilding in the Yorktown area (Figure 4).

Only nine structures have either moderate or high vulnerability to coastal hazards and sea-level rise at COLO. Only one of these structures, the Jamestown Visitor Center has an optimizer band of 1 (within FMSS), and three have an asset priority index (API, in FMSS) greater than 70 (Glasshouse Factory, Jamestown Historic Research Center, and Glasshouse Factory Ruins Shelter). The nine moderate or high vulnerability structures have a current replacement value (CRV, in FMSS) of almost $13 million. Two of these structures, the Archer Cottage and Outbuilding are considered historic within FMSS.

Forty transportation assets have either moderate or high vulnerability at COLO (Table 4). While none of these assets have an optimizer band of 1 (from FMSS), 31 of the 40 have an API greater than 70. However, it should be noted that this includes 9 segments of the Colonial Parkway, which is technically listed as a single asset within FMSS. The 40 transportation assets with moderate or high vulnerability have a CRV of $434 million, including the cost of the Colonial Parkway as one asset. If CRV is divided into equal portions for each segment of the Colonial Parkway, the total CRV for the high and moderate assets is reduced to $351 million. Seventeen of the 40 high or moderate vulnerability assets are considered historic in FMSS (9 of which are segments of the Colonial Parkway).

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

Assets	High Vulnerability		Moderate Vulnerability		Low Vulnerability		Minimal Vulnerability		Total #
	#	%	#	%	#	%	#	%	
Structures	4	5%	5	6%	5	6%	63	82%	77
Transportation	19	15%	21	17%	20	16%	65	52%	125
All COLO Assets	**23**	**11%**	**26**	**13%**	**25**	**12%**	**128**	**63%**	**202**

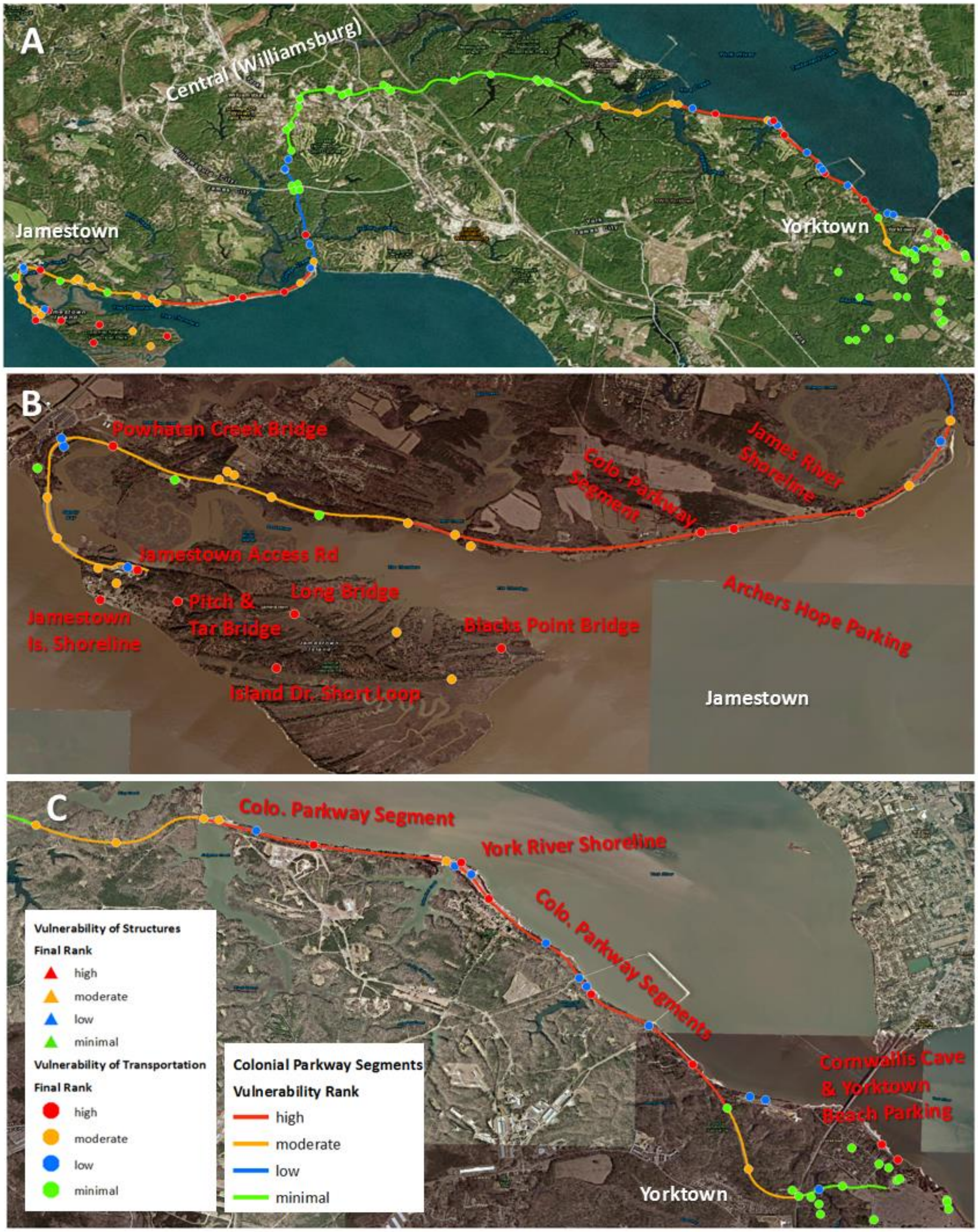

Figure 3. Vulnerability results for transportation assets at COLO. A) Results for all transportation assets at COLO, highlighting the three primary areas of the park: Jamestown, Central (Williamsburg), and Yorktown. B) Results for assets in the Jamestown area of the park. C) Results for assets in the Yorktown area of the park. Background is aerial imagery from the ESRI streaming layer.

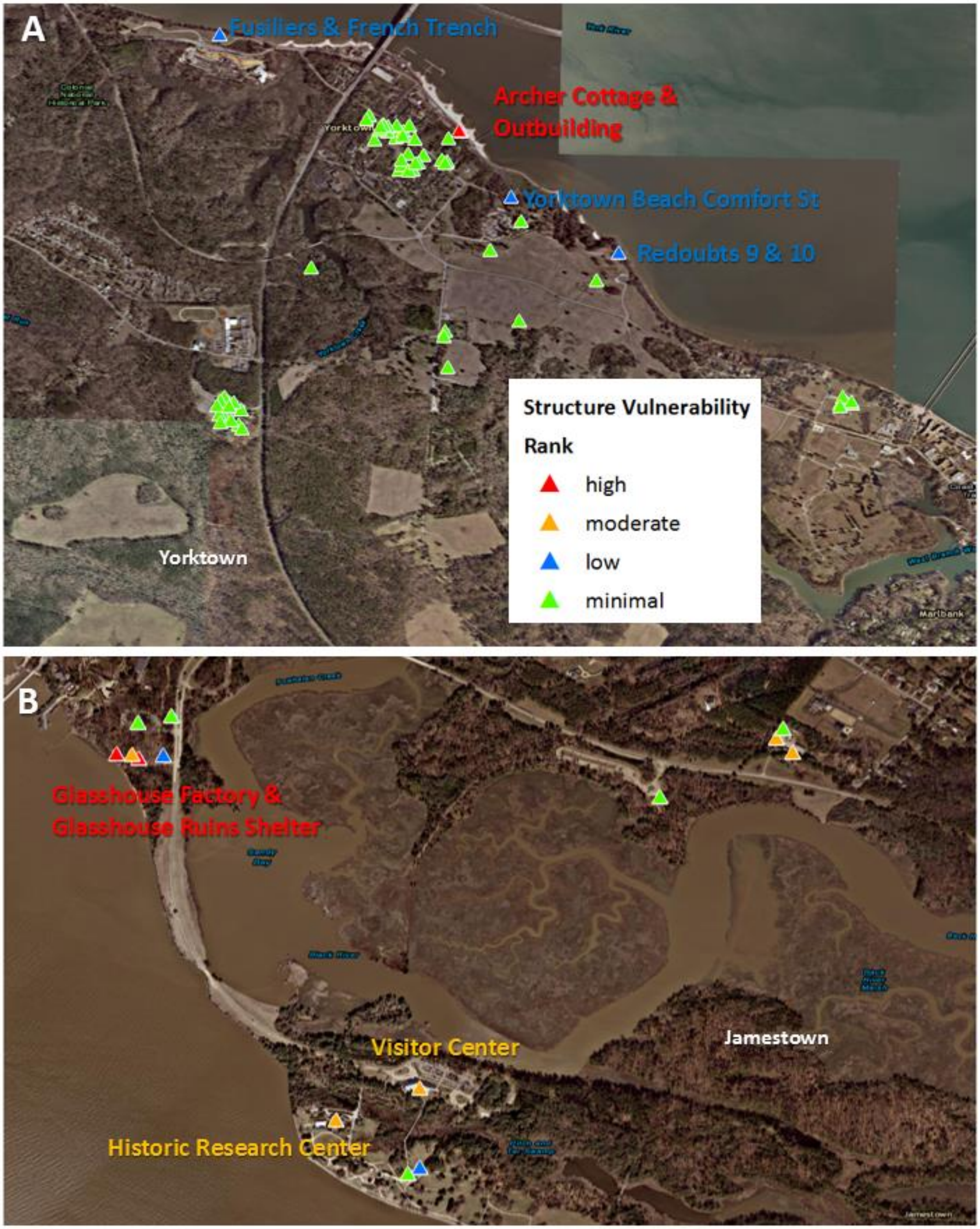

Figure 4. Vulnerability results for structures at COLO. A) Results for structures in the Yorktown area of the park. B) Results for structures in the Jamestown area of the park. Background is aerial imagery from the ESRI streaming layer.

Unique Factors & Considerations

Erosion & Coastal Proximity:

For shorelines without erosion rate data (ocean, estuarine, or developed areas) a simple **coastal proximity buffer** is applied. The coastal proximity buffer distance applied 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. Proximity buffers were used for the shoreline of COLO. Shoreline digitizing was done using the ESRI streaming layer at a scale of 1:2500.

Storm Surge Data:

The SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model that is utilized for the storm surge indicator 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. Therefore, the surge data included in the exposure analysis (the SLOSH MOM) represents the maximum *potential* surge conditions of a Category 3 storm.

Roads at COLO:

The Colonial Parkway is one of the high priority assets at COLO, and runs over 20 miles from the south to the north end of the park. In order to acquire sensitivity data for the roads at COLO, this one road was divided into segments. These segments were based on several factors, primarily exposure level and connectivity/access to other park assets. The Colonial Parkway was divided into 15 segments (Figure 5). 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 by determining whether a significant portion of the road (approximate percentage) is within the zone, or whether a critical portion is in the zone (e.g., major intersection or essential section).

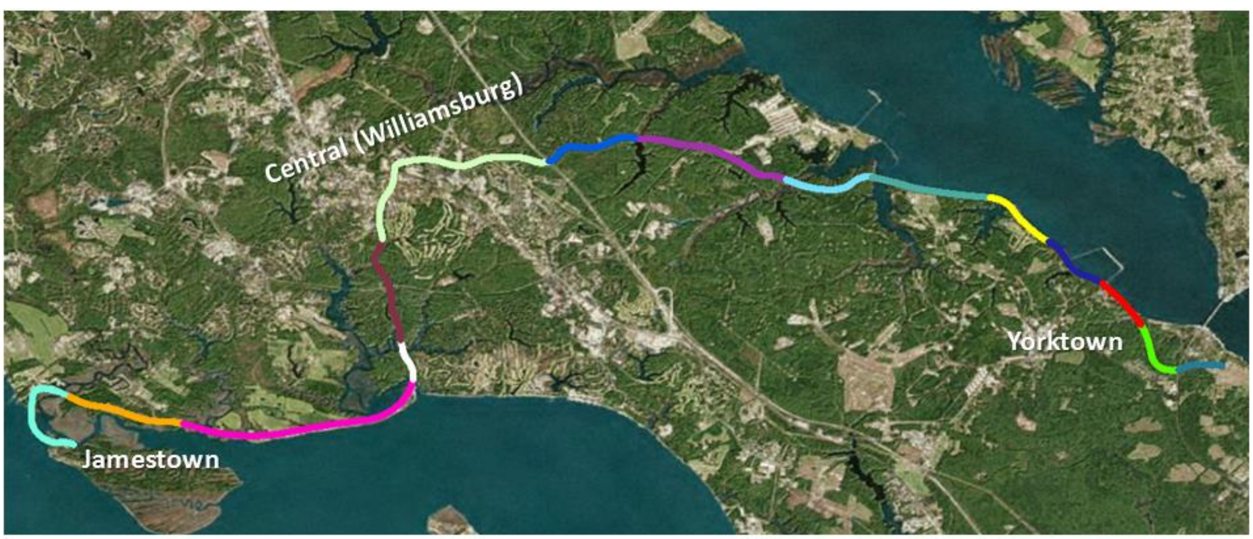

Figure 5. Colonial Parkway segments used for this analysis (15 total, each a different color).

Vulnerability Assessment 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 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 climate change. 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

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

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 generally 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 by the park 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 9).

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