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

New Bedford Whaling National Historical Park
Roger Williams National Memorial
Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment
April 2019

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

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Cover Photo: New Bedford Whaling Museum at NEBE (Photo credit: Program for the Study of Developed Shorelines at Western Carolina University).

This Page: Entrance sign at ROWI (Photo credit: Program for the Study of Developed Shorelines at Western Carolina University).

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Contents

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Executive Summary

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

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

A total of 22 structures and 5 transportation assets were included in the vulnerability assessment of New Bedford Whaling National Historical Park and Roger Williams National Memorial (NEBE-ROWI). The Wharfinger Building and the Bourne Counting House are the only buildings with moderate or high vulnerability to coastal hazards and sea-level rise at NEBE-ROWI. These buildings have the highest exposure scores of any assets, which combined with moderate sensitivity, yields higher vulnerability. In addition to being high vulnerability, the Wharfinger Building also has a high priority to the park. Three transportation-related assets have a moderate or high exposure to coastal hazards and sea-level rise, including the Waterfront Park, the SW Corner State Pier, and Route 18. The SW Corner State Pier, which has high vulnerability, also has a high priority to the park.

Approximately three-quarters of assets (70%) at NEBE-ROWI have low vulnerability to coastal hazards and sea-level rise, while 11% of assets have minimal vulnerability (i.e., not located in any exposure zone) to the coastal hazards in this study. Exposure (i.e., location) is the primary influence on vulnerability at NEBE-ROWI, as all assets have a uniform sensitivity ranking of moderate.

Vulnerability Assessment Products & Deliverables

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

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

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

Digital Data Sources

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

2. Sea-Level Rise – Climate Change Response Program (CCRP): Sea-level rise data for the year 2050 were provided by the NPS CCRP. A full publication related to this product can be found on the NPS website (https://www.nps.gov/subjects/climatechange/sealevelchange.htm) and metadata is available. WCU utilized the 2050 sea-level rise inundation model (IPCC 8.5 Representative Concentration Pathway).

3. Surge (SLOSH) – Climate Change Response Program (CCRP) – Storm surge data were provided by NPS CCRP; full publication related to this product can be found on the NPS website (https://www.nps.gov/subjects/climatechange/sealevelchange.htm) and metadata is available. These data were provided to WCU as a geodatabase by CCRP, and WCU utilized the C3M_km3, which represents a category 3 mean tide surge model. The shapefile was further edited by WCU to only show area of inundation.

4. Erosion/Coastal Proximity - For shorelines without erosion rate data, a simple coastal proximity buffer is applied. These proximity buffers comprise the erosion indicator zone for NEBE-ROWI. The shoreline was digitized using the ESRI streaming layer at scale of 1:2500.

Introduction & Project Description

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

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

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

Vulnerability = Exposure + Sensitivity + Adaptive Capacity

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

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

Vulnerability = Exposure + Sensitivity

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

General Protocol Methodology

The **Coastal Hazards and Sea-Level Rise Asset Vulnerability Assessment Protocol** has four primary steps: 1) Exposure Analysis and Mapping, 2) Sensitivity Analysis, 3) Vulnerability 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 sea-level rise exposure (to the year 2050). The exposure analysis uses data imported into a Geographical Information System (GIS), as exposure is directly dependent on location relative to mapped hazard data. Assets located within an exposure indicator hazard zone (e.g., tsunami hazard zone) are assigned a higher score than assets located outside the zone. Scores for each indicator are then summed and binned to get a total exposure score. Final exposure scores fall into one of four ranking categories (based on the number of exposure zones): minimal exposure (asset does not lie within any mapped zone), low exposure (1 zone), moderate exposure (2-3 zones), and high exposure (4-5 zones).

Table 1. NEBE-ROWI specific hazards and data sources for the exposure indicators.

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

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

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

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

Unique Factors & Considerations

Each park has a unique set of considerations based on the geologic setting and the available data. At NEBE-ROWI, the unique factors are: 1) the use of images, reports, and data from two historic storms (1938 and 1954) to supplement the historic flooding exposure indicator, 2) the use of a coastal proximity buffer to compensate for a lack of shoreline erosion data, and 3) a major portion of FMSS-listed assets for NEBE are occupied by entities other than NPS.

Historic Storms

NEBE-ROWI has been historically flooded by two Category 3 hurricanes of note: the 1938 Great New England Hurricane, and Hurricane Carol in 1954. Historical images and reports from these storms, as well as maps from the University of Rhode Island's (URI) STORMTOOLS website, were used to supplement the record of historical flooding reported by park staff.

The 1938 Great New England Hurricane remains the deadliest and most powerful hurricane in New England history, and the storm of record for NEBE-ROWI. The storm made landfall on Long Island, NY on September 21, 1938, coincident with the autumnal equinox and full moon. The resulting storm surge was over 13 feet in downtown Providence (Figure 1). Likewise, Hurricane Carol made landfall on Long Island on August 31, 1954, coincident with high tide. The surge was over 12 feet in downtown Providence.

Both NEBE and ROWI are protected by storm surge barriers that were built in response to these major flooding events. These barriers are designed to protect the city from surge of roughly 20 feet. However, research at URI has shown that when closed for a prolonged time, there may be an increased risk of precipitation-based river flooding. This engineering was factored into the sensitivity results.

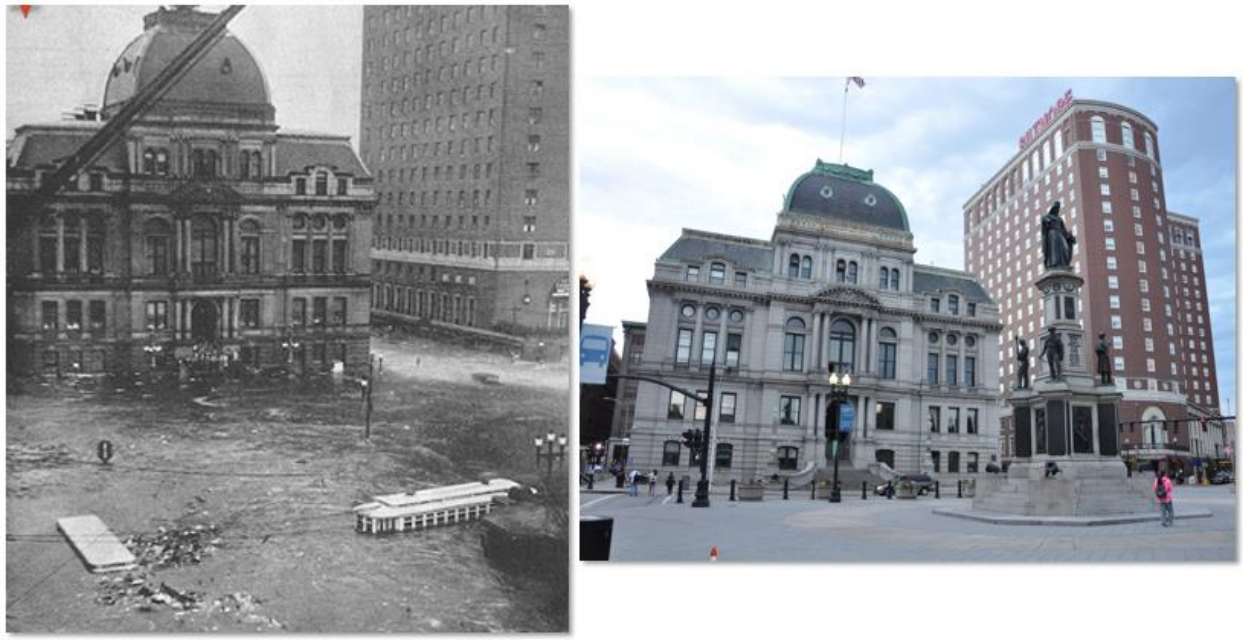

Figure 1. Left: The 13-foot storm surge from the 1938 Great New England Hurricane in Providence near City Hall and the Biltmore Hotel – note people on steps of City Hall awaiting rescue (Photo credit: Wikipedia.org). Right: City Hall and the Biltmore Hotel today (Photo credit: Program for the Study of Developed Shorelines at Western Carolina University).

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 accommodates an erosion rate up to 1 meter/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) time frame of this analysis. Proximity buffers were used for the shoreline of NEBE-ROWI. Shoreline digitizing was done using Geographic Information Systems (GIS) at a scale of 1:2500.

NEBE Occupancy:

Over half of the NEBE assets listed in FMSS are not occupied by the NPS. Instead, these assets are occupied by NPS partners, private organizations, and the state of Massachusetts. This adds a layer of complexity to decisions regarding certain park assets, and collaboration with these entities will be necessary when addressing vulnerability and adaptation to coastal hazards.

Results Summary & Discussion

A total of **22 buildings** and **5 transportation assets** (parking lots, sidewalks, landscapes/parks, and piers) were included in the vulnerability assessment of NEBE-ROWI. Also, the results for this vulnerability assessment represent a time frame of approximately 35 years (to the year 2050). Specific scores for these factors are reported (alongside FMSS data) for each individual asset in the supplied Excel datasheets; final exposure and vulnerability results are also provided as GIS maps and layers.

Exposure Results

A notable result of the exposure analysis of NEBE-ROWI assets is that only 11% of all assets (both structures and transportation) have high exposure to coastal hazards and sea-level rise, while the majority (70%) have low exposure (Table 2, Figure 2). Two assets (7%) have moderate exposure, and three assets (11%) have minimal exposure using this protocol, which means the asset did not fall within ***any*** of the mapped exposure hazard zones (flooding, storm surge, erosion/coastal proximity, sea-level rise, and historical flooding – see Vulnerability Assessment Methodology section of this document). Exposure is directly dependent on location; thus, if an asset is located beyond the influence of a coastal hazard, its exposure is diminished.

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

Assets	High Exposure		Moderate Exposure		Low Exposure		Minimal Exposure		Total #
	#	%	#	%	#	%	#	%	
Structures	1	5%	1	5%	17	77%	3	14%	22
Transportation	2	40%	1	20%	2	40%	0	0%	5
All Assets	**3**	**11%**	**2**	**7%**	**19**	**70%**	**3**	**11%**	**27**

Among structures, the highest exposure assets were the Wharfinger Building (high exposure) and the Bourne Counting House (moderate exposure). This is largely due to their proximity to the coastline, which placed them in the FEMA AE flood and erosion zones. Each of these assets was also reported to have been flooded by storms in the past. The two high exposure transportation assets at NEBE-ROWI are the Waterfront Park and the SW Corner State Pier. Both assets are in each mapped hazard zone except the sea-level rise hazard zone, and were reported as flooded in the past.

Figure 2. Example of exposure results at NEBE-ROWI. Background is aerial imagery from ESRI streaming layer.

Sensitivity Results

The sensitivity results for all NEBE-ROWI assets (structures and transportation) show all assets have moderate sensitivity to coastal hazards and sea-level rise (Table 3). All assets at NEBE-ROWI received an unfavorable score for the flood damage potential indicator (assets are not elevated), as well favorable scores for the condition and protective engineering indicators. Only two assets, the Corson Building and Custom House, were reported as storm resistant. Over three-fourths of the structures were reported as being damaged historically by flooding (Figure 3), while no transportation assets were reported as historically damaged.

Table 3. NEBE-ROWI 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	0	0%	19	100%	0	0%	19	3
Transportation	0	0%	5	100%	0	0%	5	0
All Assets	**0**	**0%**	**24**	**100%**	**0**	**0%**	**24**	3

*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.

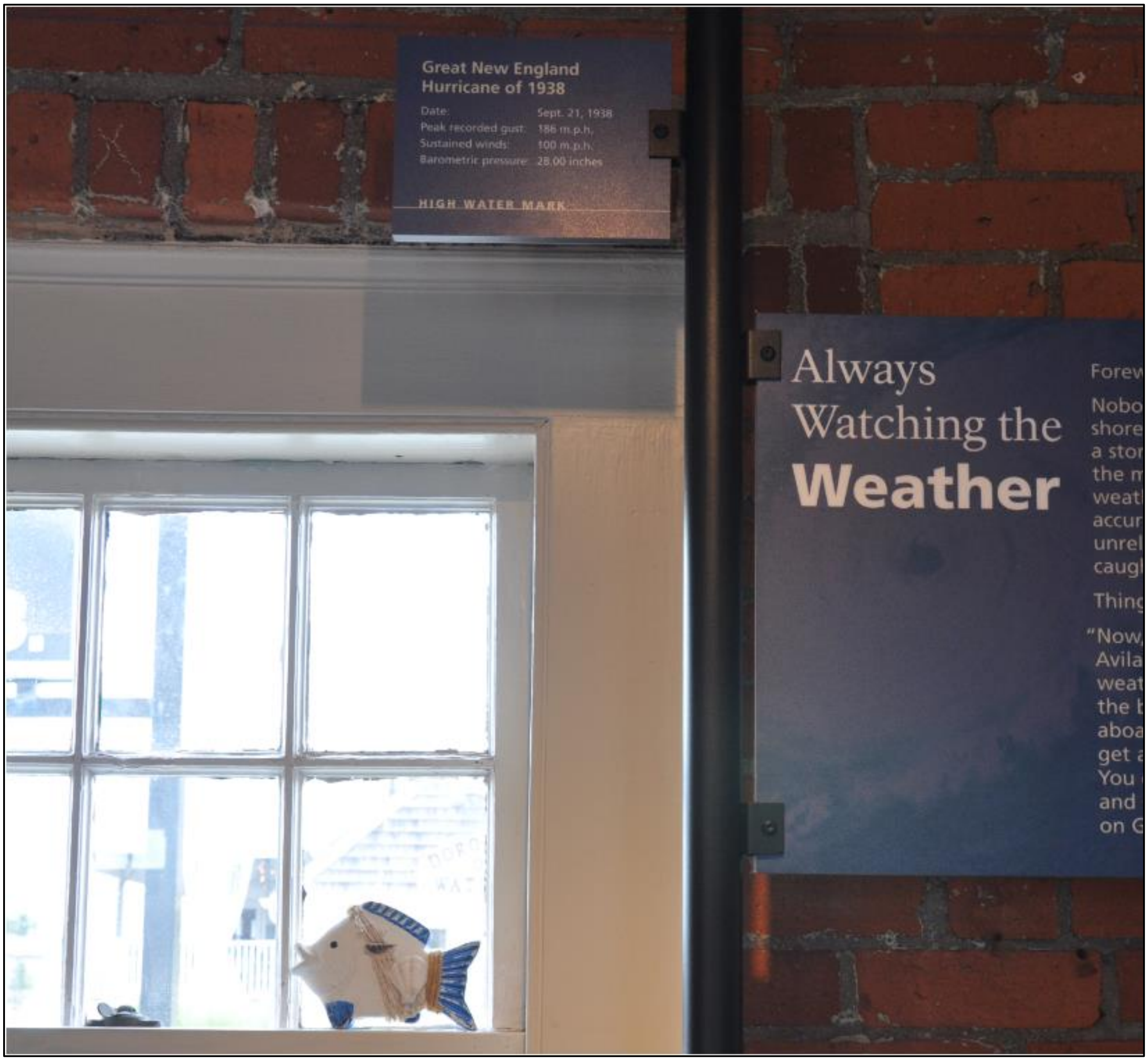

Figure 3. Great New England Hurricane of 1983 high water mark within the Wharfinger Building at NEBE (Photo credit: Program for the Study of Developed Shorelines at Western Carolina University). The water mark sign is located above a window frame inside the building. In addition to the Wharfinger Building, many other park assets were flooded and damaged during this event.

Vulnerability Results

Almost three-quarters of assets (70%) at NEBE-ROWI have low vulnerability to coastal hazards and sea-level rise, while 11% of assets have minimal vulnerability (i.e., not located in any exposure zone) to the coastal hazards in this study (Table 4). Exposure (i.e., location) is the primary influence on vulnerability at NEBE-ROWI, as all assets have a uniform sensitivity ranking of moderate (compare scores in Tables 2 and 4).

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

Assets	High Vulnerability		Moderate Vulnerability		Low Vulnerability		Minimal Vulnerability		Total #
	#	%	#	%	#	%	#	%	
Structures	1	5%	1	5%	17	77%	3	14%	22
Transportation	2	40%	1	20%	2	40%	0	0%	5
All Assets	**3**	**11%**	**2**	**7%**	**19**	**70%**	**3**	**11%**	**27**

The Wharfinger Building and the Bourne Counting House are the only structural assets with moderate or high vulnerability to coastal hazards and sea-level rise. These buildings have the highest exposure scores of any assets, which combined with moderate sensitivity, yields higher vulnerability. In addition to having high vulnerability, the Wharfinger Building also has a high priority to the park (Asset Priority Index within FMSS = 83). Three transportation-related assets have a moderate or high vulnerability to coastal hazards and sea-level rise, including the Waterfront Park, the SW Corner State Pier, and Route 18. The SW Corner State Pier also has a high priority to the park (Asset Priority Index within FMSS = 92).

Overall, 81% of NEBE-ROWI assets have either minimal or low vulnerability using this methodology (Table 4, Figure 4). However, there are several key 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 that has minimal exposure to multiple factors will inherently have a lower overall exposure, and thus, vulnerability. Also, an asset may have high vulnerability to one of these hazards but a low or moderate vulnerability to all five hazards when combined.

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. The same protocol will be used to increase the reliability of the vulnerability results.

3) Although NEBE-ROWI have no roads within FMSS, access to many park assets depends on transportation corridors that are not owned by NPS (e.g., nearby state and city roads). Some low or moderate vulnerability assets could be safe from flooding (and sea-level rise), but rendered inaccessible by many of these routes. Other coastal parks have similar issues that relate to ownership or jurisdiction of the transportation leading to NPS-owned assets and resources, necessitating coordination (e.g., additional collaborative vulnerability studies) with regional stakeholders, landowners, and partners.

Figure 4. Mapped vulnerability results for select NEBE-ROWI assets (not all assets are labeled, see Excel sheets for full results). Background is aerial imagery from ESRI streaming layer.

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:

- Coastal Adaptation Strategies Handbook, Chapter 6: Facility Management: https://www.nps.gov/subjects/climatechange/coastalhandbook.htm
- 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