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

Olympic National Park

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

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

Contents

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Cover Photo Credit: Photo taken at OLYM by Program for the Study of Developed Shorelines at Western Carolina University.

NPS 149/154047, August 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 assesses the vulnerability of infrastructure to multiple coastal hazards (i.e., erosion, flooding, storm surge, sea-level rise, and historical flooding), over a 35-year planning horizon (2050). Unlike natural resource vulnerability, which combines three metrics (exposure, sensitivity, and adaptive capacity), the newly developed method for assessing infrastructure includes only exposure and sensitivity to coastal hazards and sea-level rise in the vulnerability score; adaptation strategies are instead examined in the context of the vulnerability results. The overall goal is to standardize the methodologies and data used, allowing managers to compare the vulnerability of coastal assets across local, regional, and national levels.

A total of 506 structures and 348 transportation assets are included in the vulnerability assessment of Olympic National Park (OLYM). Well over three-fourths (86%) of all assets at OLYM have minimal vulnerability to coastal hazards and sea-level rise, while 10% have low vulnerability, 4% have moderate vulnerability, and only 1% have high vulnerability. The relatively large number of minimal vulnerability assets at OLYM is due to the fact that most are situated well inland and at higher elevations. In fact, most low and minimal vulnerability assets are within the inland mountainous regions of the park, with elevations up to 7,000 feet. The high and moderate vulnerability assets are primarily within the Kalaloch and Mora areas of the park.

The disproportionately large number of inland and high elevation assets at OLYM makes it somewhat challenging to evaluate the vulnerability trends in the coastal areas of the park. Examining just the coastal areas of OLYM (Ozette, Mora, Kalaloch, and Hoh Oil City), the vulnerability statistics show one-fifth (20%) have minimal vulnerability (compared to over three-fourths for the entire park). Also, more than half (54%) of the assets in these coastal areas have low vulnerability, 21% have moderate vulnerability, and 5% have high vulnerability.

The moderate and high vulnerability structures at OLYM have a combined current replacement value (in the NPS asset database) of approximately $33 million, which is only about 18% of the total value of structures analyzed at the park. For transportation assets, approximately $61 million are high or moderate vulnerability (3% of all transportation assets analyzed). However, this transportation value may be slightly skewed as the replacement values listed in the NPS asset database represent the **entire** road or trail, as opposed to solely the portion that is high vulnerability. Therefore, the actual value of transportation assets with high vulnerability is likely smaller. For example, the Mora-Rialto Beach Road has high vulnerability; however, only a portion of this road is within multiple exposure hazard zones.

None of the structures at OLYM have both high vulnerability and high priority to the park (asset priority index > 70, within the NPS asset database), but one high priority transportation asset has high vulnerability: the Trail System at Kalaloch. However, it must be noted again that like roads, only a small portion of this trail system is highly vulnerable.

Vulnerability Assessment Products & Deliverables:

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

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

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

Digital Data Sources

1. FEMA Flood Zones – Utilized the preliminary FEMA FIRM maps for Clallam and Jefferson Counties. Clallam County preliminary data was acquired from the State of Washington and Jefferson County preliminary data from FEMA's Preliminary Map Service Center. 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 and metadata is available. Description provided by CCRP (used 2050 data):

   "Sea-level rise estimates are taken from the United States Army Corps of Engineers (USACE) Sea-Level Change Curve Calculator. The nearest tide gauge included in this calculator was determined for each park unit. The base year for the USACE calculator is 1992. However, the calculator allows the project start year to be set as desired. For this model, the project start year is set to 1988 to match the values to the elevation based on NAVD88. The calculator determines low, intermediate, and high sea-level change projections for the tide gauge at intervals determined by the user….Once these projections are retrieved, they are fed into a simple bathtub inundation model with the USGS NED digital elevation model to determine projected inundation for the study area."

3. Tsunami Inundation Hazard Zones – Utilized draft tsunami inundation zones (Cascadia L1 model scenario) provided by Washington State Department of Natural Resources (WA DNR). Only some portions of the Kalaloch, Mora, and Hoh Oil City areas were covered by the draft data sent to WCU. Additional areas of the state are currently being mapped by WA DNR.

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 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 evaluated to determine an asset's coastal hazard and sea-level rise exposure (to the year 2050). The exposure analysis utilizes data imported into a Geographical Information System (GIS), as exposure is directly dependent on location relative to mapped hazard data. Assets located within an exposure indicator hazard zone (e.g., the tsunami zone) are assigned a higher score than assets located outside the zone. Scores for each indicator are summed and binned to get a total exposure score. Final exposure scores fall into one of four 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. OLYM specific hazards and data sources for the exposure indicators.

Exposure Indicators	OLYM Specific Hazard	OLYM Data Source
Flooding Potential	1% annual flood ± velocity/waves	Preliminary FEMA Flood Zones (VE or AE/A)
Extreme Event Flooding	Tsunami hazard zone	Washington DNR Draft Modeling
Sea-Level Rise Inundation	2050 sea-level rise	NPS-specific sea-level rise modeling
Shoreline Change	Erosion & coastal proximity	Cliff edge and proximity buffers
Reported Coastal Hazards	Historical flooding	Park questionnaire

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

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

Unique Factors: Each park has a unique set of conditions based on the data available and the geologic setting. At OLYM, the primary unique factors affecting the analysis include: 1) the use of preliminary FEMA data, 2) the use of the cliff edge and a proximity buffer in place of erosion rate data, 3) a poorly mapped sea-level rise layer in some locations, and 4) the lack of a contiguous tsunami hazard zone along the coast. A more detailed description of these factors, including how they affected the results for OLYM, are presented later in the report, in the section titled: Unique Factors & Considerations.

Results Summary & Discussion

A total of **506 structures** (buildings, amphitheaters, shelters, and sheds) and **348 transportation assets** (roads, bridges, primary trails, parking lots, and waterfront systems) were included in the vulnerability assessment of OLYM. The term "asset" will be used in this document to represent any structure or transportation infrastructure listed in FMSS, regardless of ownership. Also, the results for this vulnerability assessment represent a time frame of approximately 35 years, to approximately 2050.

This document provides a general and brief summary of the assessment methodology and results for exposure, sensitivity, and vulnerability of structure and transportation assets at OLYM. 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 most notable result of the exposure analysis at OLYM is that 86% of all assets (structures and transportation) have minimal exposure to coastal hazards and sea-level rise (Table 2). Minimal exposure within this protocol means that the asset did not fall within **any** of the mapped exposure hazard zones (flooding, tsunami, erosion/coastal proximity, sea-level rise, and reported coastal hazards – see Vulnerability Assessment Methodology towards end of document). These results are due to most park assets being located at higher elevations, well beyond most coastal hazards. Only a few assets at OLYM have either high (<1 %) or moderate (4%) exposure; approximately 10% are low exposure.

The tsunami hazard zone affects the most assets of any hazard analyzed within this study (Figure 1). In fact, all of the low exposure assets at OLYM are those located **only** within the tsunami zone. The cliff retreat/erosion buffer zone created for OLYM was the next most significant exposure indicator for OLYM. The 2050 sea-level rise inundation layer did not affect any of the assets at the park, as most of the infrastructure along the coastline is situated at higher elevations.

Table 2. OLYM 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	< 1%	25	5%	72	14%	408	81%	506
Transportation	4	1%	10	3%	10	3%	324	93%	348
All OLYM Assets	**5**	**< 1%**	**35**	**4%**	**82**	**10%**	**732**	**86%**	**854**

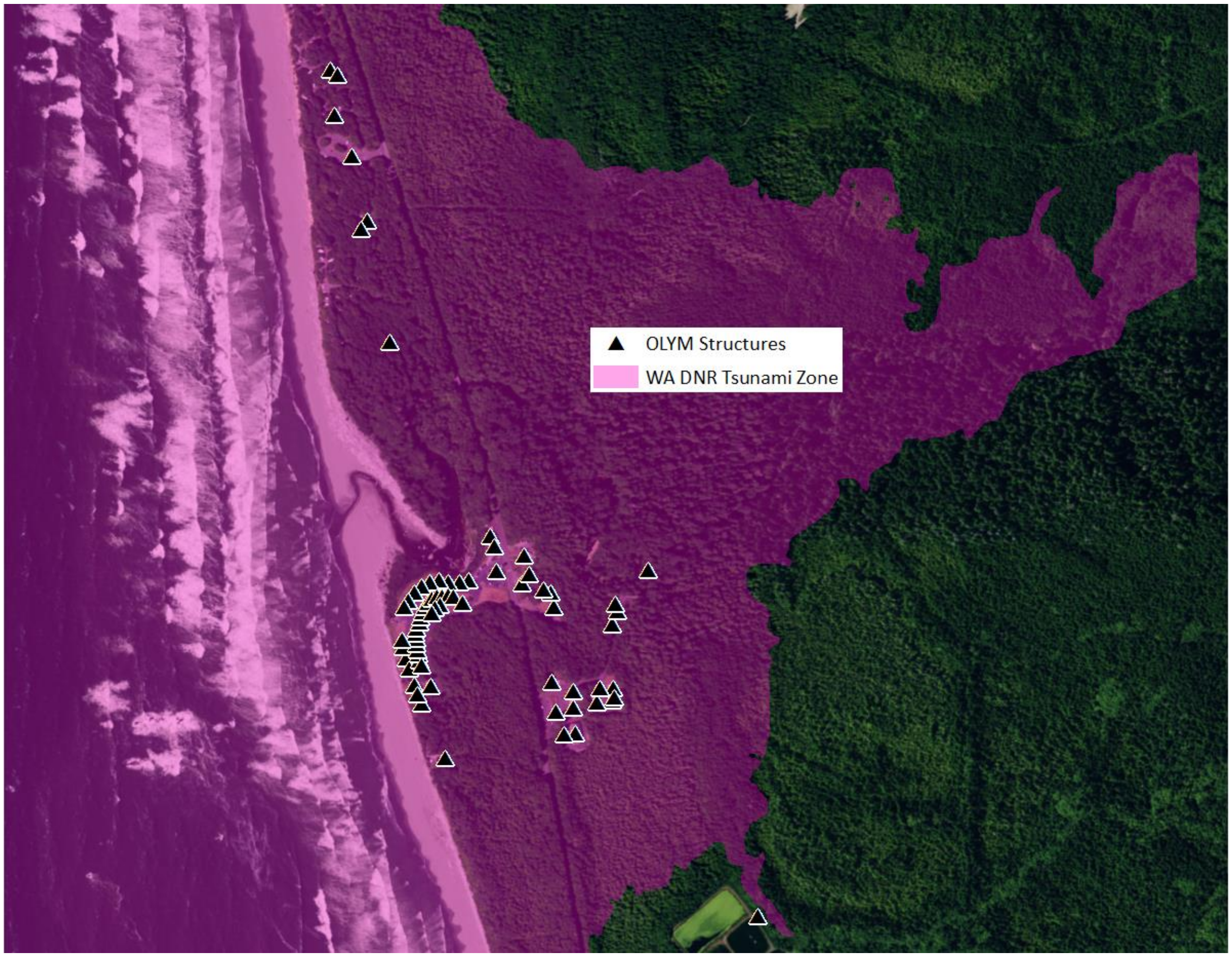

Figure 1. Example of the tsunami hazard zone (draft WA DNR modeled inundation) in the Kalaloch portion of the park. Not all assets are shown or labeled. Background is aerial imagery from the ESRI streaming layer.

Sensitivity Analysis:

The sensitivity results for all OLYM assets (structures and transportation) show that the majority (85%) of assets analyzed have moderate sensitivity and 15% have high sensitivity to coastal hazards and sea-level rise (Table 3). None of the assets analyzed have low sensitivity. However, most (86%) of the assets at the park were not analyzed for sensitivity, as they were either outside of all exposure zones or only within the tsunami zone (See Unique Factors and Conditions for more information). The mix of moderate and high sensitivity scores for assets analyzed at OLYM is primarily due to assets not being elevated, not built to storm resistant standards, and not being protected by an engineered structure.

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

Assets	High Sensitivity		Moderate Sensitivity		Total # Analyzed	Null Sensitivity (Tsunami-Only)	Excluded* (min. exposure)
	#	%	#	%			
Structures	3	12%	23	88%	26	72	408
Transportation	3	21%	11	79%	14	10	324
All OLYM Assets	**6**	**15%**	**34**	**85%**	**40**	82	750

* No assets at OLYM have a low sensitivity. The null sensitivity assets are those only in the tsunami exposure zone and not scored for sensitivity.

Vulnerability Calculation:
Well over three-fourths (86%) of all assets at OLYM have minimal vulnerability to coastal hazards and sea-level rise, while only 1% have high vulnerability, 4% have moderate vulnerability, and 10% have low vulnerability (Table 4). The high number of minimal vulnerability assets at OLYM is due to the fact that most are situated well inland and at high elevation. In fact, most assets are within the inland mountainous region of the park, with elevations up to 7,000 feet. Only a few areas of the park are along the coast, including Kalaloch, Mora, Ozette, and Hoh Oil City (Figure 2).

The high and moderate vulnerability assets are primarily within the Kalaloch and Mora areas of the park. High vulnerability structures include the Backcountry Toleak Point Shelter, Mora Rialto Beach Comfort Station, and the Mora Rialto Beach CXT Vault Toilet. The high vulnerability transportation assets include the Mora Waterfront System, Dickey River Bridge, Mora Rialto Beach Paved Road, Parking Area Mora Rialto Beach Paved, Hoh Oil Unpaved Road, and the Trail System at Kalaloch (Figures 3 and 4).

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

Assets	High Vulnerability		Moderate Vulnerability		Low Vulnerability		Minimal Vulnerability		Total #
	#	%	#	%	#	%	#	%	
Structures	3	<1%	23	5%	72	14%	408	81%	506
Transportation	5	1%	9	3%	10	3%	324	93%	348
All OLYM Assets	**8**	**1%**	**32**	**4%**	**82**	**10%**	**732**	**86%**	**854**

The disproportionately high number of inland and high elevation assets at OLYM makes it somewhat challenging to evaluate the vulnerability trends in the coastal areas of the park. Table 5 shows the vulnerability statistics for only the coastal areas of OLYM: Ozette, Mora, Kalaloch, and Hoh Oil City (Figure 2). The results show that within the coastal areas of the park, only one-fifth (20%) are minimal vulnerability (compared to 86% for the entire park). Also, more than half (54%) of the assets have low vulnerability, 21% have moderate vulnerability, and 5% have high vulnerability (Table 5).

Table 5. OLYM Coastal Areas* Vulnerability Results Summary.

Assets	High Vulnerability		Moderate Vulnerability		Low Vulnerability		Minimal Vulnerability		Total #
	#	%	#	%	#	%	#	%	
Structures	3	3%	23	20%	72	63%	17	15%	115
Transportation	5	13%	9	24%	10	26%	14	37%	38
All OLYM Assets	**8**	**5%**	**32**	**21%**	**82**	**54%**	**31**	**20%**	**153**

*Only the areas of Ozette, Mora, Kalaloch, and Hoh Oil City. Sum of percentages may not equal 100 due to rounding.

The moderate and high vulnerability structures at OLYM have a combined current replacement value (CRV; from FMSS) of approximately $33 million, which is roughly 18% of the total CRV of structures analyzed at the park. For transportation assets, approximately $61 million are high or moderate vulnerability (3% of all transportation assets analyzed). However, this transportation number may be slightly skewed as the replacement values listed in FMSS represent the **entire** road or trail, as opposed to solely the portion that has high vulnerability. Therefore, the actual CRV of transportation assets with high vulnerability is likely smaller. For example, the Mora – Rialto Beach Road has high vulnerability; however, only a portion of this road is within multiple exposure hazard zones.

None of the structures at OLYM have both high vulnerability and high priority (asset priority index [API] in FMSS > 70), but one high priority transportation asset has high vulnerability: the Trail System at Kalaloch. However, it must be noted again that like roads, only a small portion of this trail system is highly vulnerable. In addition, three high vulnerability transportation assets have an API of 65: Mora-Rialto Beach Paved Road, Mora Rialto Beach Paved Parking Area, and Hoh Oil Unpaved Road.

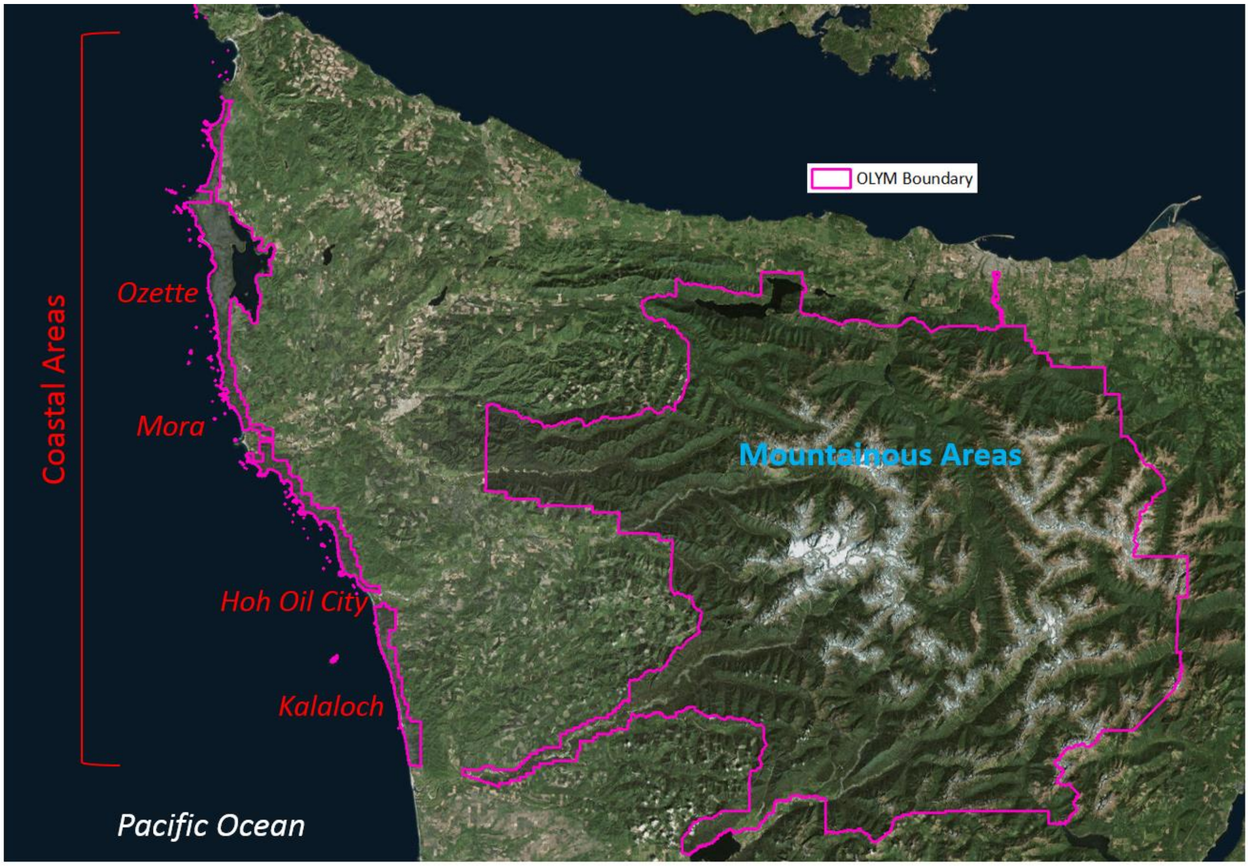

Figure 2. Map of OLYM boundary and coastal areas. Notice most of the land area in the park is well inland (mountainous areas). Background is aerial imagery from the ESRI streaming layer.

Overall, 86% of OLYM assets have minimal vulnerability to coastal hazards and sea-level rise using this methodology (Table 4, Figures 3 and 4). However, there are several important caveats to the vulnerability assessment and results:

1) This methodology is meant to assess the vulnerability of a park to coastal hazards and climate change factors combined (i.e., erosion, flooding, tsunamis, sea-level rise, and historical flooding; see indicator list in Vulnerability Assessment Methodology section). Therefore, a park or section of park that has minimal exposure to multiple factors will inherently have a lower overall exposure, and thus, vulnerability.

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

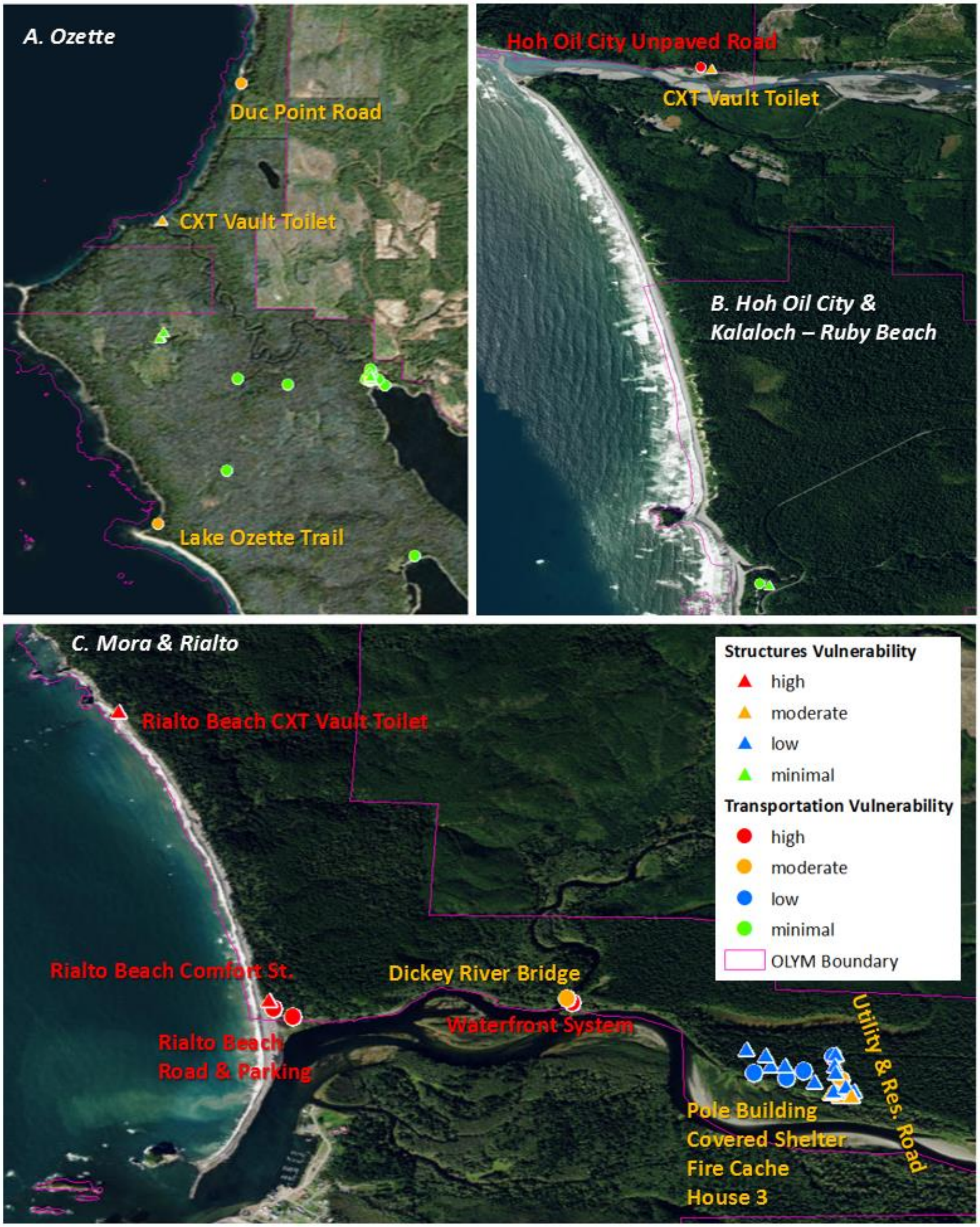

Figure 3. Example of vulnerability results at OLYM. Not all areas of the park are shown, and only select assets are labeled. A) Lake Ozette area of park. B) Hoh Oil City and Kalaloch – Ruby Beach areas of the park. C) Mora and Rialto Beach areas of the park. Background is aerial imagery from the ESRI streaming layer.

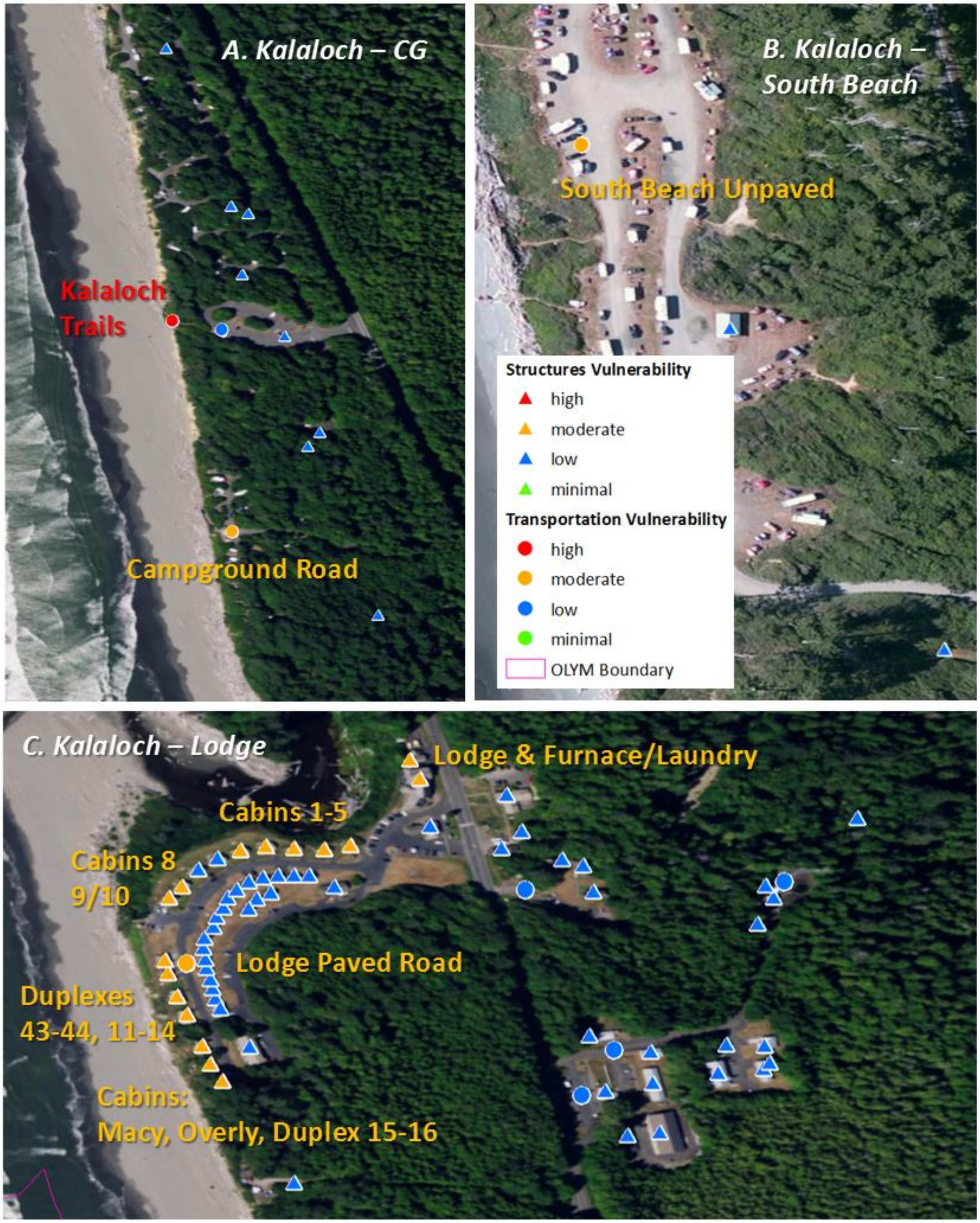

Figure 4. Example of vulnerability results at OLYM. Not all areas of the park are shown, and only select assets are labeled. A) Kalaloch – Campground area of park. B) Kalaloch – South Beach area of the park. C) Kalaloch – Lodge and Administration area of the park. Background is aerial imagery from the ESRI streaming layer.

Unique Factors & Considerations

FEMA Flooding Data:

Preliminary FEMA data was utilized for all coastal areas of OLYM, as both Clallam and Jefferson counties have preliminary, updated maps available (preliminary as of August 1, 2017). Clallam County preliminary data was acquired from the State of Washington and Jefferson County preliminary data from FEMA's Preliminary Map Service Center.

Erosion, Coastal Proximity, & Cliff Retreat:

Many national parks along the west coast of the U.S. have steeply sloping 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 rocks). In addition, it can be extremely difficult to separate how much shoreline change is due to wave erosion and how much is triggered by precipitation (or other factors). In these cases, cliff retreat data (when available) are utilized in place of erosion rate data.

Figure 5. Example of the simple coastal proximity buffer (purple) and cliff base (red line) for OLYM (South Beach area). Background is aerial imagery from the ESRI streaming layer.

However, detailed cliff retreat rate data does not exist for the undeveloped shorelines of OLYM. Therefore, a simple **coastal proximity buffer** was applied to the cliff base (Figure 5). The coastal proximity buffer distance applied is 35 meters, which can accommodate an erosion/retreat 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, including erosion, within the 35 year timeframe of this analysis. Shoreline (cliff base) digitizing was done using the ESRI streaming world imagery layer at a scale of 1:2500.

Sea-Level Rise Data:

The NPS-specific sea-level rise layer used for the exposure analysis in this study is an inundation model that projects sea-level rise in the park to the year 2050. Metadata (provided by NPS CCRP) for this model states: "Sea-level rise estimates are taken from the United States Army Corps of Engineers Sea-Level Change Curve Calculator. The nearest tide gauge included in this calculator was determined for each park unit….The calculator determines low, intermediate, and high sea-level change projections for the tide gauge at intervals determined by the user. Once these projections are retrieved, they are fed into a simple bathtub inundation model with the USGS NED digital elevation model to determine projected inundation for the study area."

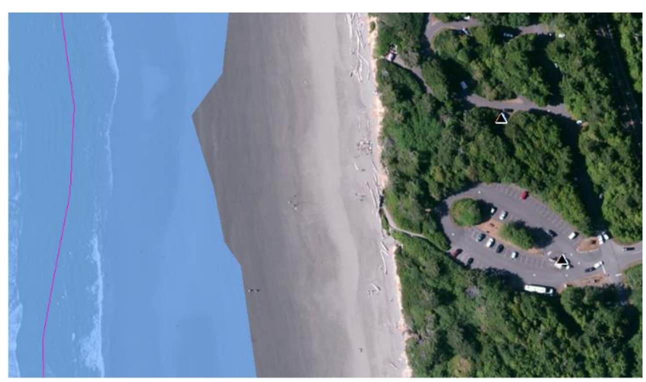

Figure 6. Example of the 2050 sea-level rise inundation model (blue) near Kalaloch Campground. Background is aerial imagery from the ESRI streaming layer.

The 2050 sea-level rise data at OLYM was not particularly well mapped in some locations, and in many areas did not reach the shoreline of current imagery (Figure 6). In fact, no assets were within the mapped sea-level rise zone. However, even with more accurate data, it is not likely that sea-level rise would affect any of the OLYM assets by 2050 because most assets are located further inland and at higher elevations. This does not mean that other resources (cultural and natural, for example) close to the coastline will not be affected by sea-level rise within this time frame.

Extreme Flooding Data:

For parks subject to tropical storms, a surge model is used for the extreme flooding indicator. For parks that do not have storm surge data (primarily west coast), an alternative data source is used, commonly either modeled extreme high water events (from CCRP, based on historic tide gage data), or modeled tsunami hazard zones (variety of sources). For OLYM, tsunami hazard zones/inundation zones (created by Washington DNR) were utilized for the extreme flooding exposure indicator. These data represent the potential tsunami inundation for the Cascadia L1 model scenario, which was described by WA DNR as:

> *"a GeoClaw numerical model for a local tsunami generated by a 9.1M Cascadia subduction zone earthquake, designated 'L1' by Witter and others in 2011. This scenario is estimated to have a 2% probability of non-exceedance in 50 years, which would be comparable to the International Building Code standard for seismic loading on structures of high importance, and provides appropriate guidance to the affected communities for siting of their significant infrastructure."*

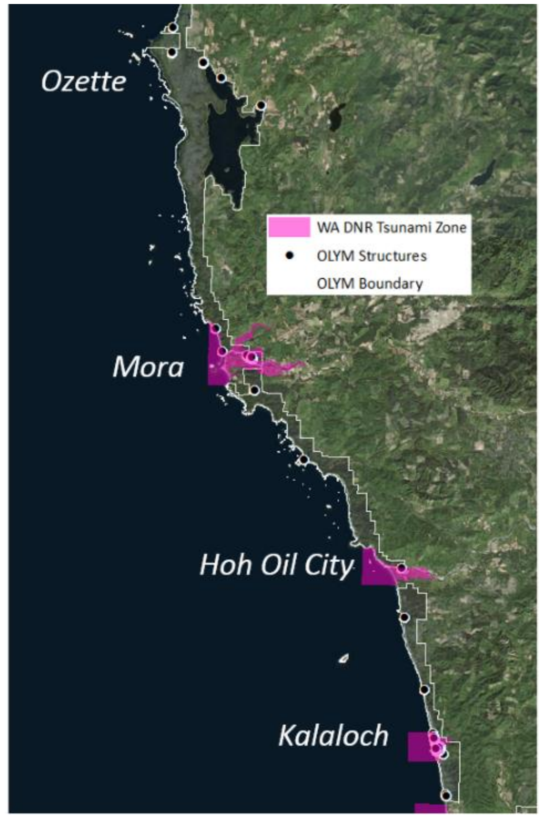

Figure 7. Extent of the draft tsunami hazard zones mapped by WA DNR (pink polygons). Background is aerial imagery from the ESRI streaming layer.

Unfortunately, only a portion of the coastline is currently covered by the draft data provided by WA DNR (Figure 7). The shoreline near Mora, Hoh Oil City, and the campground/lodge area of Kalaloch was covered by the tsunami data. Assets near Ozette, Kalaloch – South Beach, Ruby Beach, and Beaches 1 – 4 did not have tsunami data. In cases where data was absent, a determination for this exposure indicator was made based on additional data and factors, such as proximity to the coast and elevation data (digital elevation maps).

Tsunami Sensitivity

This assessment examines vulnerability to five exposure indicators, and sensitivity, in turn, is evaluated in the context of all exposure factors combined, not just tsunamis. Thus, any asset that was **only** in the tsunami exposure zone was given a null value for sensitivity, as the sensitivity indicators (flood damage potential, storm resistance, condition, historical damage, and protective engineering) do not readily apply when evaluating tsunamis alone. Therefore, for assets at OLYM exposed only to tsunamis, the vulnerability score is dependent on exposure (i.e. location) alone, as sensitivity has little relevance.

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 sea-level rise. Standard exposure indicators have been determined; 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 6 summarizes these indicators, as well as common data sources for each.

Table 6. 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 7 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 7. 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 8 below describes each indicator, including the description, rationale, and scoring.

Table 8. 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 9. 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