National Park Service
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Natural Resource Stewardship and Science

Climate Change Vulnerability Assessments in the National Park Service

An integrated review for infrastructure, natural resources, and cultural resources.

Natural Resource Report NPS/NRSS/CCRP/NRR—2022/2404

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ON THIS PAGE
Raven/Shark Totem Pole, Sitka National Historical Park

ON THE COVER
Bodie Island Lighthouse, Cape Hatteras National Seashore

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Natural Resource Report NPS/NRSS/CCRP/NRR—2022/2404

Editors: Katie McDowell Peek[1], Blair R. Tormey[1], Holli L. Thompson[1], Alan C. Ellsworth[2], and Cat Hawkins Hoffman[2]

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

[2]U.S. National Park Service
Climate Change Response Program
Fort Collins, CO 80525

June 2022

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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Please cite this publication as:

Peek, K.M., B. R. Tormey, H.L. Thompson, A. C. Ellsworth, and C.H. Hoffman (editors). 2022. Climate change vulnerability assessments in the National Park Service: An integrated review for infrastructure, natural resources, and cultural resources. Natural Resource Report NPS/NRSS/CCRP/NRR—2022/2404. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/nrr-2293650.

NPS 999/181593, June 2022

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Executive Summary

Climate changes are affecting virtually all National Park Service units and resources, and an assessment of climate vulnerabilities is important for developing proactive management plans to respond appropriately to these changes and threats. Vulnerability assessments typically evaluate exposure and sensitivity of the assessment targets and evaluate adaptive capacity for living resources. Chapters in this report review and evaluate climate vulnerability assessments of National Park Service units and resources including infrastructure, natural resources, and cultural resources. Striking results were the diversity of approaches to conducting vulnerability assessments, the small number of vulnerability assessments for National Park Service cultural resources, and the large differences in the "state of the science" of conducting assessments among the three resource groups. Vulnerability assessment methodologies are well established for evaluating infrastructure and natural resources, albeit with very different techniques, but far less is known or available for designing and/or conducting cultural resources assessments.

Challenges consistently identified in the vulnerability assessments, or the chapters were:

- Limited capacity of park staff to fully engage in the design and/or execution of the vulnerability assessments. Most park staff are fully engaged in on-going duties.
- Inconsistent use of terms, definitions, and protocols, sometimes resulting in confusion or inefficiencies.
- Discovering and acquiring National Park Service vulnerability assessments because results were inconsistently archived.
- Aligning results with park needs due to differences in level of detail, scope, and/or resolution, or format(s) for reporting results.

Best practices and recommendations identified in multiple chapters were:

- Ensure that vulnerability assessments are designed to match parks' needs, and that results are reported in ways that inform identified management decisions.
- Prioritize resources to be thoroughly assessed so effort is directed to the most important threats and resources.
- Evaluate all components of vulnerability (not just exposure).
- Explicitly and systematically address uncertainty, recognizing the range of climate projections and our understanding of potential responses.
- Identify and, where possible, focus on key vulnerabilities that most threaten conservation or management goals.
- Embrace partnerships and engage others with necessary expertise. Good vulnerability assessments usually require expertise in a broad range of subject areas.

Glossary

Adaptation (Infrastructure Chapter): anticipating the effects of climate change (or natural hazards) and taking steps to avoid or minimize damage.

Adaptation strategy (Infrastructure Chapter): A strategy/action taken to reduce or manage an asset's vulnerability (exposure/sensitivity) to natural hazard or climate change impacts.

Adaptive capacity:

- **IPCC 2014:** The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.
- **Infrastructure and Natural Resources Chapters:** The ability of a species or system to adjust to, moderate, or cope with climate change (or natural hazards).
- **Cultural Resources Chapter:** The ability of human managers and systems to adjust the use and management of a given resource.

Asset (Infrastructure Chapter): Specific infrastructure or facility owned by an agency (e.g., a road, building, or parking lot), often used when discussing facility databases. This term is sometimes employed for museum property and other cultural resource types.

Climate change (US GCRP 2019): Changes in average weather conditions that persist over multiple decades or longer. Climate change encompasses both increases and decreases in temperature, as well as shifts in precipitation, changing risk of certain types of severe weather events, and changes to other features of the climate system.

Climate change adaptation (IPCC 2014): The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.

Climate model (IPCC 2014): A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions, and feedback processes, and accounting for some of its known properties. The climate system can be represented by models of varying complexity.

Climate projections (IPCC 2014): The simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative-forcing scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.

Climate Scenarios (Natural Resources Chapter): The use of a range of projected climate conditions which result from selecting different global climate models and/or emissions scenarios/pathways.

Criticality (Infrastructure Chapter): The importance or significance of an asset (functional, historical, financial, etc.).

Cultural resources (NPS 2006): These include archeological resources, cultural landscapes, ethnographic resources, historic and prehistoric structures, and museum collections.

Explicit NRVA (Natural): Studies that specifically claim to be evaluating "climate vulnerability", "climate exposure", or "climate sensitivity" and use at least one of those terms.

Exposure:

1. **Gross et al. 2014:** A measure of the character, magnitude, and rate of climatic changes a target species or system may experience. This includes exposure to changes in direct climatic variables (e.g., temperature, precipitation, solar radiation) as well as changes in related factors (e.g., sea-level rise, water temperatures, drought intensity, ocean acidification).
2. **Infrastructure Chapter:** Whether the resource of interest is located in an area that experiences the hazard or impacts of climate change.
3. **Natural Resources Chapter:** The extent to which climate change or a climate-driven change in environment is likely to be experienced by a species or system (Dawson et al. 2011).
4. **Cultural Resources Chapter:** The degree to which a given resource is expected to be affected by a stressor, threat, or hazard.

Extrinsic adaptive capacity (Natural Resources Chapter): Factors external to the organism or system that affect its ability to adapt.

Hazard (IPCC 2014): The potential occurrence of a natural or human-induced event, trend, or impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, provision of services, ecosystems, and environmental resources.

Impact (Infrastructure Chapter): The severity or consequence of a natural hazard or climate change stressor. Commonly used in risk assessments.

Implicit NRVA (Natural Resources Chapter): Studies that never use the term "vulnerability" in a climate change context, but their purpose is to evaluate potential future changes in one or more park natural resources due to climate change. These may use the terms climate disruption, climate impacts, or climate assessment to describe their efforts. Implicit climate change vulnerability assessments do not frame climate impacts in terms of exposure, sensitivity, or adaptive capacity, though they implicitly address one or more of these.

Indicator based vulnerability assessments (Tonmoy et al. 2014): An assessment based on attributes or characteristics of a system, rather than on direct impacts. Most often used for social systems or infrastructure, where e.g., economics or maintenance history may relate to vulnerability.

Indicators (Infrastructure Chapter): Factors or data used to represent and evaluate vulnerability (exposure or sensitivity).

Infrastructure: Buildings, roads, utilities, equipment and other structures or facilities.

Intrinsic adaptive capacity (Natural Resources Chapter): The inherent ability of a species or system to adapt to climate change.

Likelihood: The chance of a specific outcome occurring, which may be estimated probabilistically.

Mitigation (IPCC 2014): A human intervention to reduce the sources or enhance the sinks of greenhouse gases.

Phenology (IPCC 2014): The relationship between biological phenomena that recur periodically (e.g., development stages, migration) and climate and seasonal changes.

Phenotypic plasticity (US GCRP 2019): The ability of an organism to change its behavior, physiology, or physical characteristics in response to its environment. This change occurs within an organism's lifetime and therefore does not require genetic change.

Proactive sensitivity (Cultural Resources Chapter): The potential of a resource to be harmed by a stressor, based on active measures undertaken by human stewards.

Probability (Infrastructure Chapter): The likelihood or frequency of an event, hazard, or stressor. Commonly used in risk assessments.

Quantitative vulnerability assessment approaches (Cultural Resources Chapter): Large-scale measurement of impacts using a spatially based approach of overlay or intersection methods to determine exposure of individual resources.

Qualitative vulnerability assessment approaches (Cultural Resources Chapter): High-resolution assessment of unique characteristics of stressors, exposure, and sensitivity. Usually informed by site- and resource-specific knowledge.

Reactive sensitivity (Cultural Resources Chapter): Inherent properties that affect the potential to be harmed by a stressor.

Resilience:

1. **IPCC 2014:** The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.

2. **Infrastructure Chapter:** The ability of a system to absorb or adapt to climate change or natural hazard stress; term is often used interchangeable with vulnerability.

Resource Stewardship Strategy (RSS) (Synthesis Chapter): An RSS (which has replaced Resource Management Plans) is a comprehensive strategy to guide and provide improved accountability for the park's multi-year cumulative monetary investment in resource stewardship. Benchmark target values (synonymous with attaining desired conditions) for an RSS's measurable indicators provide park management with assessment measures for current resource condition relative to desired condition, and the effectiveness of management actions towards achieving or maintaining a desired condition.

Risk:

1. **US GCRP 2019:** Threats to life, health and safety, the environment, economic well-being, and other things of value. Risks are often evaluated in terms of how likely they are to occur (probability) and the damages that would result if they did happen (consequences).
2. **Infrastructure Chapter:** The probability (likelihood, frequency) and impact (severity, consequence) of a natural hazard or climate change stressor.

Risk assessment (Jones 2001): The process of identifying the magnitude or consequences of an adverse event or impact occurring as well as the probability that the event or impact will occur.

Scale: Geographic extent of the study; the scope or study area.

Scale (Infrastructure Chapter): The amount of detail or specificity in the analysis; the level or resolution at which the analysis is performed. Infrastructure vulnerability assessments commonly include either 1) spatial scale (e.g., asset-site, community, regional, national), and/or 2) infrastructure scale (e.g., component, asset, systems).

Scenario (Gross et al. 2016): A coherent, internally consistent and plausible description of a possible future state of a system. Similarly, an *emissions scenario* is a possible storyline regarding future emissions of greenhouse gases. Scenarios are used to investigate the potential impacts of climate change: emissions scenarios serve as inputs to climate models; climate scenarios serve as inputs to impact assessments.

Scenario planning (Infrastructure and Natural Resources Chapters): A formal planning process that seeks to develop a series of alternative plausible futures that differ depending on one or more critical uncertainties.

Sensitivity:

1. **IPCC 2014:** The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise).

2. **Infrastructure Chapter:** How a resource will fare when exposed to a natural hazard or climate change stressor.
3. **Cultural Resources Chapter:** Measures a resource's susceptibility to harm from an exposure type.
4. **Natural Resources Chapter:** The degree to which the survival, functioning, or performance of a system or species is likely to be impacted by a given change in climate.

Stressor (IPCC 2014): Events and trends, often not climate-related, that have an important effect on the system exposed and can increase vulnerability to climate related risk.

Vulnerability:

1. **IPCC 2007:** Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.
2. **IPCC 2014:** The propensity or predisposition to be adversely affected [by climate change]. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.
3. **Natural Resources Chapter:** The degree to which a system or a component of that system is likely to be harmed by a particular hazard and is often described as being a function of three distinct elements—exposure, sensitivity, and adaptive capacity.
4. **Infrastructure and Cultural Resources Chapter:** The sum of exposure and sensitivity.

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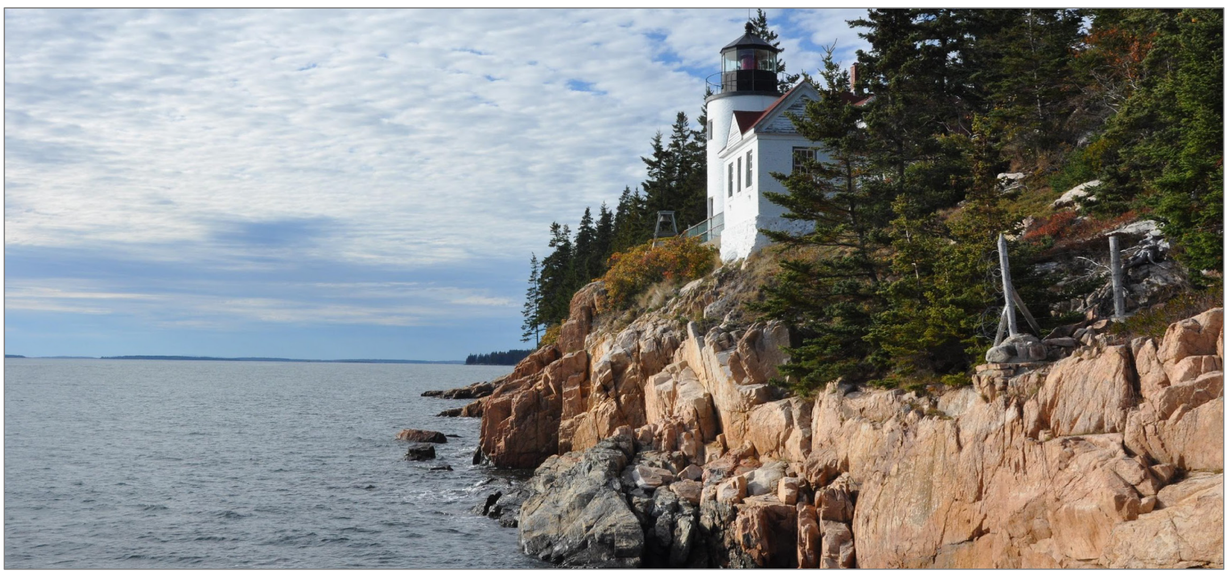
Chapter 1: Overview and Synthesis of National Park Service Vulnerability Assessments

John E. Gross[1], Blair R. Tormey[2], Katie McDowell Peek[2], Holli L. Thompson[2], Julia L. Michalak[3], and Robert S. Young[2]

[1]U.S. National Park Service
Climate Change Response Program
Fort Collins, CO 80525

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

[3]School of Environmental and Forest Sciences
University of Washington
Seattle, WA 98195



Lighthouse at Acadia National Park. (©PROGRAM FOR THE STUDY OF DEVELOPED SHORELINES, WESTERN CAROLINA UNIVERSITY)

Please cite this chapter as:

Gross, J.E., B.R. Tormey, K.M. Peek, H.L. Thompson, J.L. Michalak, and R.S. Young. 2022. Chapter 1: Overview and Synthesis of NPS Vulnerability Assessments. Pages 1-25 *in* Peek, K.M., B. R. Tormey, H.L. Thompson, A. C. Ellsworth, and C.H. Hoffman (editors). 2022. Climate change vulnerability assessments in the National Park Service: An integrated review for infrastructure, natural resources, and cultural resources. Natural Resource Report NPS/NRSS/CCRP/NRR—2022/2404. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/nrr- 2293650.

1.0 Executive Summary

Vulnerability assessments of National Park Service units and resources including infrastructure, natural resources, and cultural resources were evaluated to better understand the "state of the science" among these resource groups. While approaches are diverse, methods for evaluating infrastructure and natural resource vulnerability assessments were found to be more well established than what is known or available for design and development of cultural resources assessments. Consistent challenges were identified along with best practices and recommendations based on this literature review.

1.1 Acknowledgments

This chapter was substantially improved by the contributions of many people. M. Rockman, R.L. Beavers, and C. Hawkins-Hoffman were instrumental to initiating this project and they provided guidance and leadership throughout the life of the project. P.L. Yu and J.J. Lawler contributed information about their chapters, and A.C. Ellsworth shepherded the documents through the review and publication process. This chapter was substantially improved by thoughtful and incisive reviews from G.W. Schuurman, M. Hilton, and S. Norton. We thank all these people and others that made this study possible.

This document was funded and developed by the National Park Service Park Climate Change Response Program, in partnership with Western Carolina University, through a Task Agreement (P16AC01773) with the Southern Appalachian Cooperative Ecosystems Studies Unit (Cooperative Agreement P14AC00882).

1.2 Acronyms

CCRP: Climate Change Response Program (NPS)

CRVA: Cultural Resources Vulnerability Assessment

IPCC: Intergovernmental Panel on Climate Change

IRMA: Integrated Resource Management Applications (NPS)

IVA: Infrastructure Vulnerability Assessment

NPS: National Park Service

NRVA: Natural Resources Vulnerability Assessment

SLR: Sea-Level Rise

VA: Vulnerability Assessment

1.3 NPS Region and Unit Codes

Region Codes

AKR: Alaska Region

IMR: Intermountain Region

MWR: Midwest Region

NCR: National Capital Region

NER: Northeast Region

PWR: Pacific West Region

SER: Southeast Region

Park Unit Codes

CAHA: Cape Hatteras National Seashore

CALO: Cape Lookout National Seashore

COLO: Colonial National Historical Park

FIIS: Fire Island National Seashore

GWMP: George Washington Memorial Parkway

1.4 Vulnerability Assessments and NPS Needs

Climate change impacts are apparent across the National Park System, and climate model projections portend increasing impacts in the future (USGCRP 2017). Proactive management of parks requires understanding how and where climate changes pose threats and hazards, and developing plans to mitigate or respond to forthcoming changes. Vulnerability assessments (VAs) help parks respond to climate changes by identifying what is at risk and why.

The National Park Service (NPS) manages a diverse array of resources and assets, including outstanding cultural and natural resources, buildings, transportation networks, recreational facilities, water and sewer infrastructure, and a broad range of visitor experiences. These resources and assets are differentially affected by climate, and there is no single method or approach to assessing climate vulnerability that can be uniformly applied across the vast geography and values that the NPS manages. In addition, practices to assess climate vulnerability and to implement climate change adaptation are developing rapidly. The difficulty of conducting assessments varies tremendously, as do the assessment targets. While VAs of natural resources and infrastructure are common (e.g., Johnson 2014), the authors of this study found few VAs relevant for cultural resources (Table 1-1). Box 1-1 provides relevant definitions of climate vulnerability and climate change adaptation.

The NPS has undertaken multiple efforts to identify and understand climate change hazards and the vulnerability of park resources and infrastructure, ranging from rapid, broad-scale (extent) desktop assessments, to multi-disciplinary, park-specific vulnerability and adaptation planning efforts. Vulnerability is being examined at all levels of the NPS, and across all disciplines and directorates. Resulting VA products were stored in a variety of different locations that often made these products difficult to discover and acquire. This created challenges for park managers and researchers to locate relevant VAs and to use the information they contained. Although there has been coordination between some VAs, others have proceeded without benefitting from insights and lessons previously learned. A more coordinated approach to assessing climate vulnerability could result in a range of benefits: improved efficiency in designing studies, more consistency in deliverables, and a greater likelihood that the VAs meet the most important information needs of parks.

Table 1-1. Summary of VA review chapters.

Chapter[A]	# Studies[B]	Stressors	Target	Classification Scheme
2: IVA	91	Natural hazards & climate change	NPS & other agencies	Exposure assessments, scenario planning studies, risk assessment, & indicator-based VAs
3: NRVA	71	Climate change	NPS (I&M units)	General assessments, broad-scale screens, systematic multi-target evaluations, & single resource or process assessments
4: CRVA	14	Climate change	NPS	Assessment of exposure, sensitivity, & vulnerability

[A] Chapter number and VA type within this document. IVA = infrastructure vulnerability assessment. NRVA = natural resources vulnerability assessment. CRVA = cultural resources vulnerability assessment.

[B] The number of VA studies evaluated in each chapter.

Box 1-1: What is climate "vulnerability" and what is climate change "adaptation"?

Vulnerability has been defined and calculated in many ways. A widely used definition is: "The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (IPCC 2007). More recently, the Intergovernmental Panel on Climate Change (IPCC 2014) modified the definition of vulnerability to place it more centrally within a hazards assessment framework, broadening the definition to "The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt." The NPS Climate Change Response Program has adopted the U.S. Global Change Research Program definition: "The degree to which physical, biological, and socio-economic systems are susceptible to and unable to cope with adverse impacts of climate change" (USGCRP 2018).

Climate change VAs are an important, early step towards planning for and implementing climate change adaptation.

Climate change adaptation is an intentional management response to observed climate changes or plausible future changes that involves identifying, preparing for (e.g., developing strategy and specific actions), and responding to (e.g., implementing actions) those changes. The desired outcome from the management response is to retain current conditions, recover from climate variations (perhaps to an altered state), or adjust to changing conditions that may include major transformation in practices or state. Adaptation may seek to "moderate harm or exploit beneficial opportunities" (IPCC 2014).

The NPS commissioned a multi-disciplinary team of researchers to identify, review, and evaluate VAs that specifically addressed NPS units and resources in an effort to improve the agency's ability to learn from previous VAs, to distill "lessons learned", and identify best practices for designing and conducting VAs. Researchers compiled and evaluated VAs produced through spring 2018, with primary goals to:

- provide an inventory and comprehensive review of the VAs conducted on infrastructure, natural resources, and cultural resources, within and relevant to the NPS,
- evaluate and articulate lessons learned from this collection of VAs, including best practices, and
- provide a central location for discovery and access to this report and the VAs used in the synthesis.

This document presents results from this review of VAs in four chapters:

5. Overview and Synthesis of National Park Service Vulnerability Assessments (this chapter),
6. A Review of Vulnerability Assessments for National Park Service INFRASTRUCTURE,
7. A Review of Vulnerability Assessments for NATURAL RESOURCES of the National Park Service, and
8. A Review of Vulnerability Assessments for CULTURAL RESOURCES of the National Park Service.

Each of the discipline-specific chapters were funded and completed independently and therefore the approach and VA selection criteria varied. All chapters represent the best available information and knowledge of the authors at the time they were written.

1.5 Useful Vulnerability Assessments

For NPS purposes, VAs need to provide actionable information that improves park management by supporting climate change adaptation. Vulnerability assessments vary in spatial scale and scope, from sites to landscapes to a global extent, and from evaluating a single species to comprehensively evaluating all park resources. Definitions of what constitutes a VA are similarly diverse. However, the highest-quality VAs consistently include:

- evaluation of exposure to explicit climate hazards or threats,
- an assessment of how climate hazards/threats affect the target(s) of the VA,
- for living resources, an evaluation of their adaptive capacity,
- observed (historical) trends and climate projections,
- spatial information (Where are values threatened? Do climate refugia exist?), and
- an explicit evaluation of uncertainty.

A VA does not need to include all possible elements to be useful to park managers, and many VAs have addressed only one or two elements of vulnerability (Thompson et al. 2015). Climate exposure, often evaluated from changes in temperature and precipitation, is the most easily and commonly evaluated component. Exposure is also the component of vulnerability that is most applicable across disciplines or sectors. The level of effort expended to assess climate factors needs to be scaled to the information needs for decisions, and to the capacity of the people who will use the information. An appropriate VA may only require a day or two of effort for a subject matter expert or may require months of work by a team of park staff and collaborators.

Vulnerability assessment results can be communicated in a wide variety of products, including tables, graphs, maps, and reports, or a combination of these elements. Results may be ranks, numerical scores, narratives, or profiles. The VAs included in this report cover a spectrum of formats; the utility of many VAs could be improved through use of minimal standards. For example, maps should be delivered in a graphic format (e.g., png) and a format that retains geographical information (e.g., geodatabase, raster, geoTIFF, geoPDF); and numerical tables should be provided in a printable format (e.g., pdf) and a machine-readable format suitable for further analysis (e.g., csv). Metadata is essential. The NPS has only recently employed these standards for products from VAs.

Context and Background of Vulnerability Assessment Frameworks and Methods

The most effective VAs are designed to contribute to and inform a planning process. Ideally, the management decision that the VA is to inform will determine the most appropriate planning process, but the design of the VA can be highly dependent on the quality and availability of data and the expertise of those who design and conduct the assessment. Figure 1-1 is a simplification of the broader context of NPS decision-making and how VAs can fit into this. Expert elicitation, structured decision making, and scenario-based planning are common—but by no means exclusive—processes used to integrate VAs into decision-making (Hoffman et al. 2014). Vulnerability assessments may be based on one or more existing frameworks, and one or more methods could be used to assess the individual components of a VA (Figure 1-1). Methods for conducting VAs are rapidly evolving (particularly for cultural resources), and many VAs use multiple methods or approaches to make the most effective use of information.

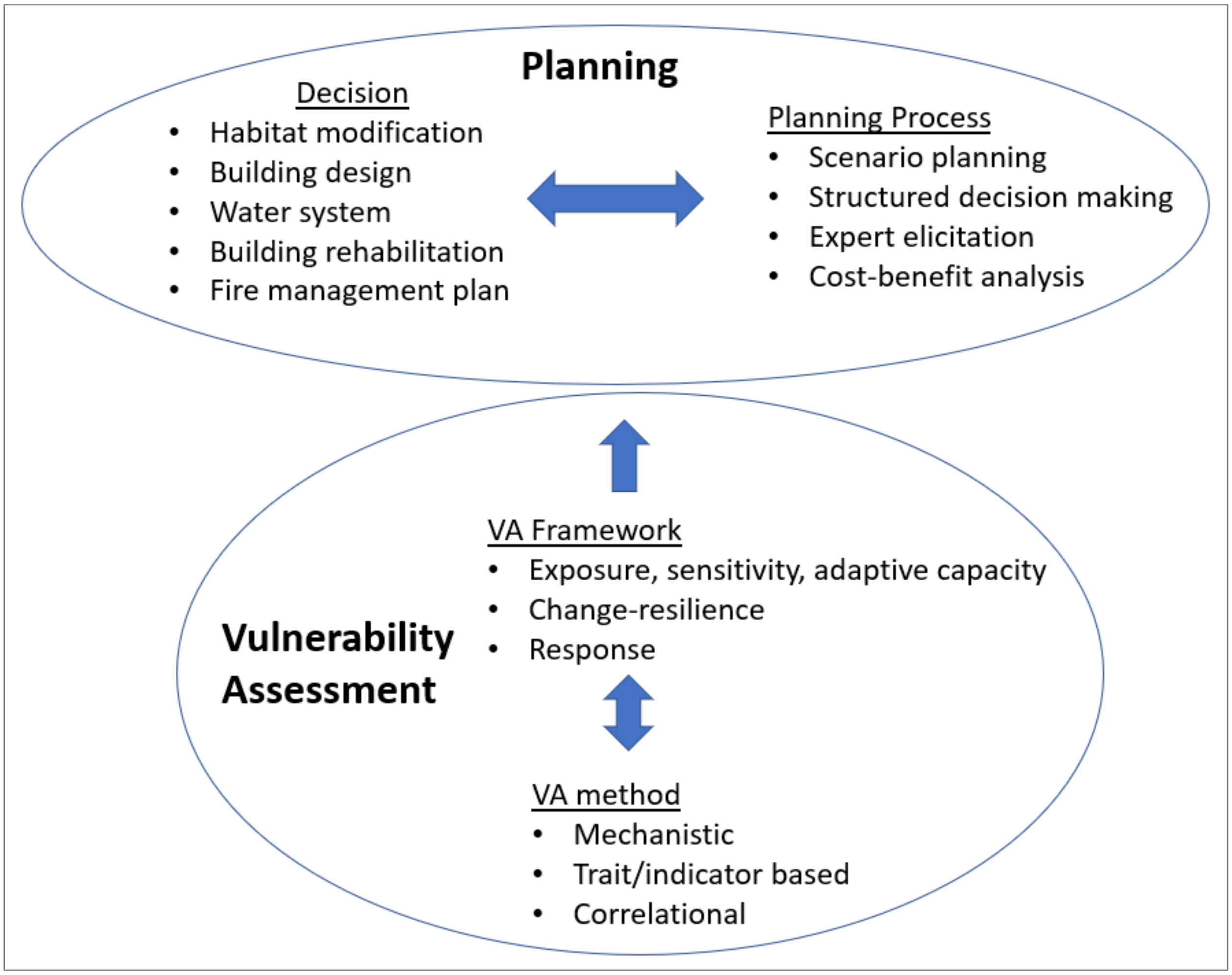


Figure 1-1. Vulnerability assessments need to be designed and conducted to support planning processes and management decisions. This figure illustrates a few of the many potential VA frameworks and methods.

The most widely used conceptual framework to assess climate vulnerability consists of climate exposure, sensitivity, and adaptive capacity (Figure 1-2; see Box 1-2). Climate impact is determined by exposure and sensitivity, and adaptive capacity moderates potential impacts (Figure 1-2). All three reviews (Chapters 2-4) stress the importance of evaluating these components of vulnerability. This three-component VA framework is readily applied to living resources and adaptive capacity is the response by the assessment target. The NPS Climate Change Response Program (CCRP) considers the concept of adaptive capacity to apply only to living resources, which have the capability to respond to a changing climate, and not to non-living resources such as buildings and infrastructure. The concept of adaptive capacity has been handled in many ways, resulting in substantial confusion. Particularly for communities or built systems, assessment of adaptive capacity has often included management responses, or the capacity of people or communities to respond to climate impacts (Turner et al. 2003). Furthermore, in practice it can be difficult to assign traits or characteristics to either sensitivity or adaptive capacity, with the result that adaptive capacity and sensitivity are sometimes lumped together (e.g., Williams et al. 2008; Young et al. 2015). Nonetheless, adaptive capacity addresses an essential component of vulnerability, and it focuses on characteristics of organisms that can be foundational to assessing vulnerability and to developing successful adaptation strategies (Thurman et al. 2020, 2022). Adaptation strategies and actions seek to reduce climate change exposure or sensitivity, or enhance adaptive capacity (of living resources) and thereby reduce impacts and vulnerability.

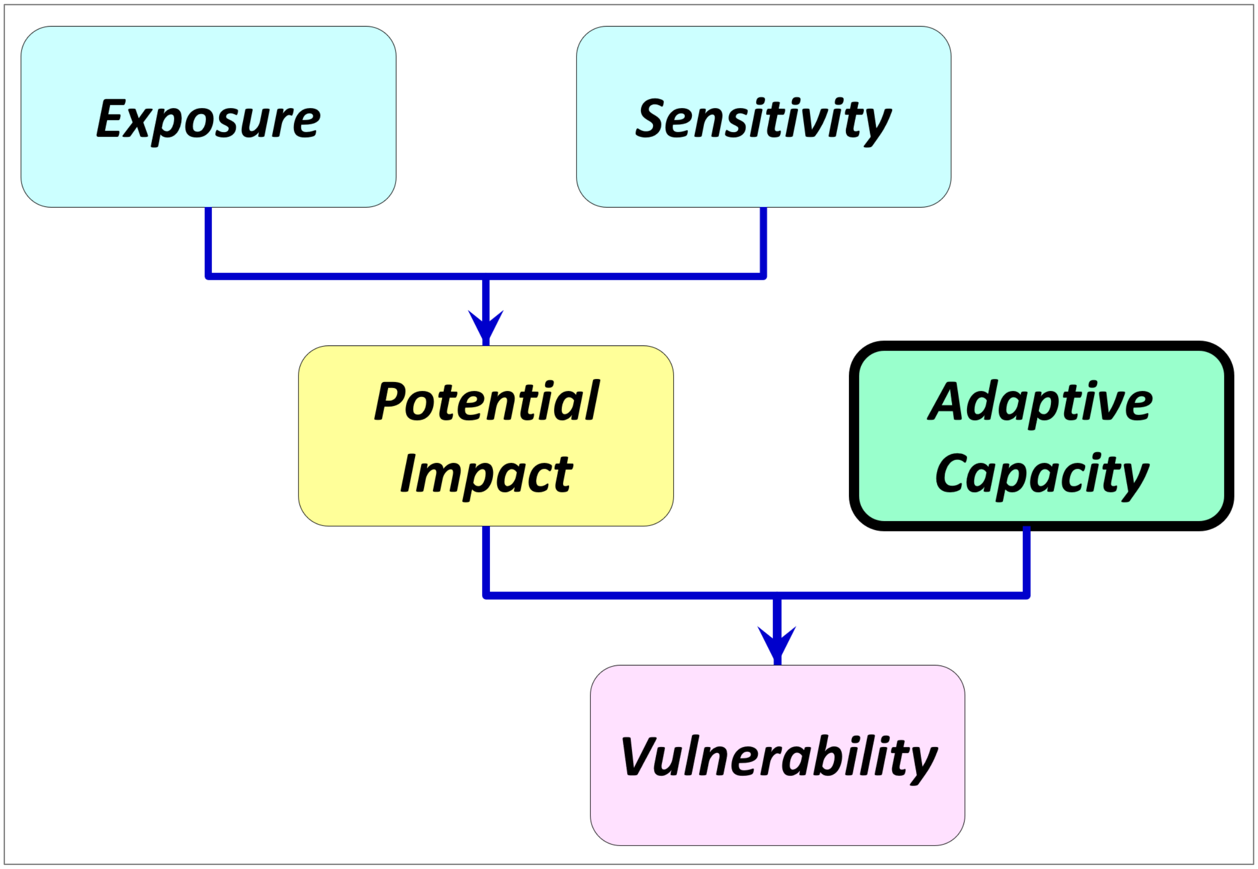


Figure 1-2. Commonly used framework for assessing climate vulnerability showing that climate impacts (negative or positive) result from exposure and sensitivity. For living resources, the impacts may be ameliorated by the adaptive capacity of the organism. See Box 1-2 for definition of terms.

Box 1-2. Components of vulnerability

Climate vulnerability is frequently evaluated by assessing the exposure, sensitivity, and adaptive capacity, as illustrated in Figure 1-2, with the components defined as:

Exposure: A measure of the character, magnitude, and rate of changes a target may experience. In the climate change context, this includes changes in climate drivers (e.g., temperature, precipitation, solar radiation) as well as changes in related factors (e.g., sea level, water temperatures, drought intensity, ocean acidification) (Gross et al. 2014).

Sensitivity: The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise) (IPCC 2014).

Adaptive Capacity: The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences (IPCC 2014). For institutions, the term applies to both the ability of the institution to adapt so as to persist in its own right and to foster adaptation among other systems, humans, or organisms.

These three terms were defined independently by the chapter authors, and the similar, but alternative, definitions used in the chapters are provided in the Glossary.

While the framework illustrated in Figure 1-2 has become a de facto standard, particularly for natural resources, many other approaches and frameworks for conducting VAs are in use. Fortini and Schubert's (2017) VA framework focused on four responses to climate change (migrate, exploit micro-refugia, tolerate, or evolve) to assess Hawaiian plants and birds (Fortini et al. 2015), including species highly important to parks. Other approaches focus on ecosystem change and resilience (Prober et al. 2012), or species/system traits (Young et al. 2015). This diversity in VA frameworks reflects the breadth in resource characteristics and differing states of knowledge and management.

Vulnerability Assessment Methods

Within each framework, a variety of methods are available to evaluate the components of vulnerability. For example, climate sensitivity of a species could be inferred by assessing the range (breadth) of climate characteristics where the species occurs, or it could be determined from extensive laboratory and field manipulations that carefully document physiological responses to a changing environment. Similarly, a building's sensitivity could be evaluated from a historical maintenance schedule and expert opinion, or from experimental applications of rainfall with measurements of the weathering of paints and wall claddings.

The VA methods in the following chapters can be roughly categorized as mechanistic, trait- or indicator-based, or correlational.

Mechanistic assessments are based on a functional understanding of processes and relationships between the VA target, climate, and other important factors that permit the investigator to predict, often quantitatively, responses to climate change. Outside of NPS, mechanistic approaches have often been used for infrastructure VAs (Chapter 2), where engineering and structural principles are well established and can be applied to assess the ability of built systems to withstand projected changes in climate exposure. Mechanistic assessments of species or habitats typically require detailed physiological, demographic, and other data that are often not available.

Trait- or Indicator-based VAs use attributes (traits, characteristics) to assess sensitivity and, where applicable, adaptive capacity of VA targets. When designed to use existing databases, indicator-based VAs can often be completed quickly and for a large number of VA targets (e.g., Pacifici et al. 2018).

Correlative assessments rely on statistical relationships between climate, other covariates, and one or more important measure(s) of the conservation target. For species, the most common measure is occurrence, and correlations between climate and occurrence are the basis for climate envelope and many species distribution models. Most correlative assessments are relatively fast and require little data. The data are often available in readily accessible databases, and an initial model may be constructed very quickly and inexpensively for many conservation targets such as species (Wu et al. 2018).

Each method has strengths and weaknesses, and a frontier in vulnerability science is developing hybrid methods that integrate or combine features to improve both the efficiency and the accuracy of forecasts. For example, Iverson et al. (2019) combined climate envelope models, a correlational method, with a trait-based assessment of climate change adaptation potential to assess climate vulnerability of 125 eastern U.S. tree species, improving evaluations over each method used independently.

Climate Futures, Scenarios, and Range of Climate Projections

Most VAs include an assessment of climate change, usually with an evaluation of both historical (observed) trends and future (projected) trends. All climate projections are associated with a range of variation. Variation in climate projections results from factors such as how climate models mathematically describe processes (e.g., cloud formation), human decisions (e.g., greenhouse gas emissions, land use), inherent system randomness (e.g., how complex wind and temperature gradients interact), and what is or is not included in the climate model (e.g., societal decisions, changes in land cover, deep ocean processes). More robust VAs explicitly address the range of variation or uncertainty[1] in climate projections.

The use of climate futures and scenarios is an increasingly common approach to address the range of variation among climate projections and the impact of climate changes on resources and values of interest (NPS 2021a). In the context of VAs, ***climate futures*** describe divergent climates that could plausibly occur at a specific place and time, and that capture the range of variation among projections (Lawrence et al. 2021). Climate futures are foundational to creating full scenarios. Scenarios incorporate climate futures to assess implications that are consequential to resources and values that are important to managers and the broader community. Although the infrastructure vulnerability assessment (IVA) chapter considers scenarios as a distinct approach to conducting VAs, climate futures and scenarios can be integrated into and support a broad range of VA approaches (NPS 2021a; Lawrence et al. 2021). The NPS recently produced guidance (NPS 2021a) describing how scenario planning can be integrated into established NPS planning processes and the Climate-Smart adaptation cycle (Stein et al. 2014).

1.6 Chapter Scope and Limitations

Authors of each chapter started with similar goals, but the availability and breadth of relevant VAs varied considerably between chapters. Table 1-1 summarizes the number and key attributes of VAs included in the analyses in each chapter. Differences in the number of studies carefully examined in each chapter were striking, ranging from 14 (CRVAs) to 91 IVAs. These numbers are broadly indicative of the maturity of VA methods for these sectors, and they particularly emphasize the dearth of VAs for cultural resources. Although the number of VAs evaluated in Chapters 2 and 3 were roughly similar, the authors of Chapter 2 (IVAs) reached well beyond NPS-focused studies to make their evaluation more inclusive and meaningful to the NPS. The infrastructure chapter included VAs conducted by local, state, federal, and international government agencies, and included other natural hazards (in addition to climate change). Vulnerability assessments from these non-NPS organizations were included because of the limited quantity and variety of NPS-specific climate change-based VAs for infrastructure. In contrast, the abundance of natural resources vulnerability assessments (NRVAs) meant that the authors of Chapter 3 (NRVAs) had to impose strict criteria to subset the available VAs to a manageable number.

Each of the chapters used different criteria for selecting the VAs that were included in their detailed analyses. The IVA and CRVA chapters focused solely on VAs that explicitly stated they were evaluating climate-change vulnerability, threats, or risks to infrastructure or cultural resources. The IVA chapter reviewed both assessments conducted for national parks and assessments from other government entities such as cities, states, and the Federal Highway Administration. The NRVA chapter included publicly available VAs for named national parks. In addition, the NRVA chapter

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[1] Here, "uncertainty" describes the statistical properties of the range of variation such as the standard deviation, and how variation can be attributed to different sources such as greenhouse gas emissions. It is not a measure of "how much we know", but closer to "how sensitive model results are to factors we know about."

also included documents that did not explicitly claim to evaluate vulnerability but did evaluate projected future changes in one or more park natural resources due to climate change. Beyond these, many studies described potential climate-change impacts to species, habitats, and ecosystems that are relevant to park resource decisions, but these studies did not explicitly identify a park or the NPS system. Given the large number of these types of assessments and studies, the NRVA chapter restricted its evaluation to those documents that explicitly stated they were evaluating the National Park System or specific named parks.

Relatively few climate change VAs evaluated in this report addressed all components of vulnerability. The evaluated VAs also lack a consistent definition or minimal threshold for what qualifies as a climate change VA (versus a consideration of a potential climate impact). This is particularly evident for studies that only assessed exposure, or even a small subset of the potentially important climate exposure variables (e.g., Monahan and Fisichelli 2014; Hansen et al. 2014; Peek et al. 2015). This lack of distinction does not affect the utility of the information in a study, but it does complicate comparisons of studies and can affect need-based prioritizations that assume all studies are equally comprehensive.

A key challenge for all investigators was locating and acquiring VAs specifically focused on NPS resources. Ensuring that all NPS-commissioned VA are archived in NPS Integrated Resource Management Applications (IRMA) would significantly improve the ability of all to discover and obtain products from VAs.

There are no established ways to categorize VAs, particularly across the broad range of NPS resources. Here, each chapter was developed independently, and classification schemes are therefore unique to each chapter (Table 1-1). With reference to Figure 1-1, the non-exclusive classification in the IVA chapter (Chapter 2) includes a higher-level planning process, two categories best described as VA frameworks, and an assessment method. The NRVA chapter (Chapter 3) categorized VAs by scale, scope, and "general" VAs that covered a range of resources in one or more parks. The CRVA review (Chapter 4) includes a conceptual diagram of tradeoffs between spatial scale and focus (scope), illustrating the use of broader-scale (but less detailed VAs) to identify priorities that would need to be addressed via more detailed (finer spatial scale) VAs. Since there were only 14 cultural resource VA studies evaluated in detail, Chapter 4 did not explicitly categorize the studies, but the authors evaluated how each study assessed exposure and sensitivity, the use of qualitative and quantitative methods, and success in meeting the stated goals of the study.

Although the use of independent VA classification schemes facilitated analysis within each chapter or discipline, it prevented any simple cross-disciplinary comparisons of results. All chapters were similar in evaluating exposure, but beyond that there was a broad range of approaches and frameworks. Some studies, particularly of infrastructure assets, focused on hazards and were clearly influenced by the existing compliance and regulatory requirement. Natural and cultural resource VAs most frequently followed the framework illustrated in Figure 1-2, but there was still a broad range of approaches. Should such a study be conducted in the future, it would be informative to develop a conceptual model such as Figure 1-1 to facilitate evaluation of different methods, frameworks, and planning processes that contribute to climate change adaptation. These could further be subdivided into studies that are quantitative/qualitative/both, and by scope and scale

1.7 Chapter Summaries

Infrastructure

Chapter 2 reviews VA approaches used to understand potential natural hazard and climate change impacts to infrastructure within the NPS, as well as other local, state, federal, and international government agencies. Over 90 documents related to infrastructure vulnerability were reviewed (Table 1-1). Four approaches characterize these IVAs: 1) exposure assessments, 2) scenario planning studies, 3) risk assessments, and 4) indicator-based VAs. This chapter also discusses common approach themes, considerations and challenges, and recommendations for assessing the climate change and natural hazard vulnerability of infrastructure, emphasizing protocols most appropriate for the NPS.

Natural Resources

Chapter 3 reviews VA approaches used to understand climate change impacts to natural resources within the NPS, specific to park units within the Inventory and Monitoring system (Table 1-1). This chapter identifies 71 studies with either an explicit or implicit goal of evaluating natural resource climate change vulnerability. From these studies, four NRVA approaches are documented: 1) general assessments, 2) broad-scale screens, 3) systematic multi-target evaluations, and 4) single resource or process assessments. This chapter examines the spatial distribution and assessment targets of NRVAs, as well as the components of vulnerability, common tools and models, and evaluation of uncertainty. Finally, this chapter recommends best practices for conducting NRVAs for national parks, and for protected areas in general.

Cultural Resources

Chapter 4 reviews VA approaches used to understand climate change impacts to cultural resources within the NPS (Table 1-1). This chapter describes and compares the goals, methods, results, and best practices of 14 CRVAs and identifies major accomplishments and missed opportunities. This chapter also summarizes the application of the components of vulnerability (exposure, sensitivity, and the unique role of adaptive capacity), identifies common geographic gaps and opportunities across the studies, and provides near-term recommendations for future efforts.

1.8 Vulnerability Assessment Review and Comparison

There are multiple similarities and differences across IVAs, NRVAs, and CRVAs, as well as in the approach of each review chapter. The following section describes these common themes, differences in approach, and use of terminology.

Scale, Scope, and Resolution

The term "scale" has a variety of connotations and uses. In this report, scale was used to refer to both the geographic extent of and the resolution, or granularity, of the analysis. The natural and cultural resources chapters typically refer to geographic extent as scale (e.g., fine or broad scale, site or regional/national scale), while the infrastructure chapter used scale to refer to the granularity of the data or analysis – what natural resource studies would typically refer to as "resolution." In this report, resolution in Chapter 2 (infrastructure) refers to assets, whereas in Chapter 4 it refers to the spatial scale (e.g., grid size) of data. "Scope" more consistently referred to the diversity of resources considered.

When scale refers to geography, broad-scale VAs are typically screening or coarse-filter studies (see Noon et al. 2009) that assess a subset of climate factors across multiple park units with a goal to identify priorities for further action. These coarse-filter studies necessarily rely on generic variables or indicators, rather than species- or asset-specific characteristics, and the resolution of data rarely aligns with that needed to design site-specific management actions. Natural resources are the most common conservation targets for coarse-filter studies, and most of these focus on exposure, which is sometimes used to drive species distribution models (e.g., Lawler et al. 2010).

Quantitative, Qualitative, and Combined Vulnerability Assessments

All three chapters discussed VA approaches that could be characterized as quantitative, qualitative, or both. We can identify a few generalizations:

- Broad-scale, coarse-screening studies are usually quantitative, and they use automated methods that process changes in temperature or other numerical metrics.
- Hazard assessment IVAs are almost by necessity quantitative because they rely on probabilities and often on engineering analyses.
- Natural Resources Vulnerability Assessments commonly combine quantitative and qualitative information, sometimes producing a specific numerical score, and sometimes a categorical ranking.
- Climate exposure is almost always a quantitative input (e.g., change in temperature, precipitation, or sea-level rise (SLR) determined from computer model), but sensitivity and adaptive capacity are often based on expert knowledge and are very frequently qualitative inputs.

1.9 Geographic Coverage

Virtually all NPS units have some information on climate exposure that is relevant to all resources from the National Climate Assessment (USGCRP 2017; 2018), IPCC reports, and similar sources (see e.g., https://toolkit.climate.gov/tools/climate-explorer). For many parks, a coarse-filter assessment of natural resource vulnerabilities based on exposure can be supplemented by regional-scale or species-focused studies such as the U.S. Forest Service regional VAs (e.g., Halofsky et al. 2018a, b; Hayward et al. 2017; Janowiak et al. 2018; Williams and Friggins 2017) and assessments of key species, trees, fish, or other taxa (e.g., Bagne et al. 2011; Cole et al. 2011; Iverson et al. 2008; Isaak et al. 2016). Because such assessments are not focused on park units, they were excluded from detailed analyses. There are currently (as of 2021) many sources of information, outside of formal VAs, that parks can use to assess climate vulnerabilities. We discuss these further below, including challenges to using this information.

Based on the subset of studies used for the analyses in Chapters 2, 3, and 4, approximately 230 NPS units (more than 50%) have not been the focus of any park-specific, detailed VA (Figure 1-3, and

Figure 1-4, “No VA” category). Large-extent, multi-park studies were excluded from the “detailed” VA category (Peek et al. 2015; Wilson 2014; all NRVA broad-scale screens; Chapter 2 of this report). The Intermountain Region (IMR), Alaska Region (AKR), and National Capital Region[2] (NCR) had the highest percentage of units lacking a detailed VA (approximately two-thirds each, Figure 1-3, and Figure 1-4). In contrast, roughly two-thirds of the Southeast Region (SER) units have been the focus of detailed VAs (only one-third of these units lack a detailed VA). Approximately half of the units within the Pacific West Region (PWR), Midwest Region (MWR), and Northeast Region (NER) had no detailed VAs at the time of the analyses (2018).

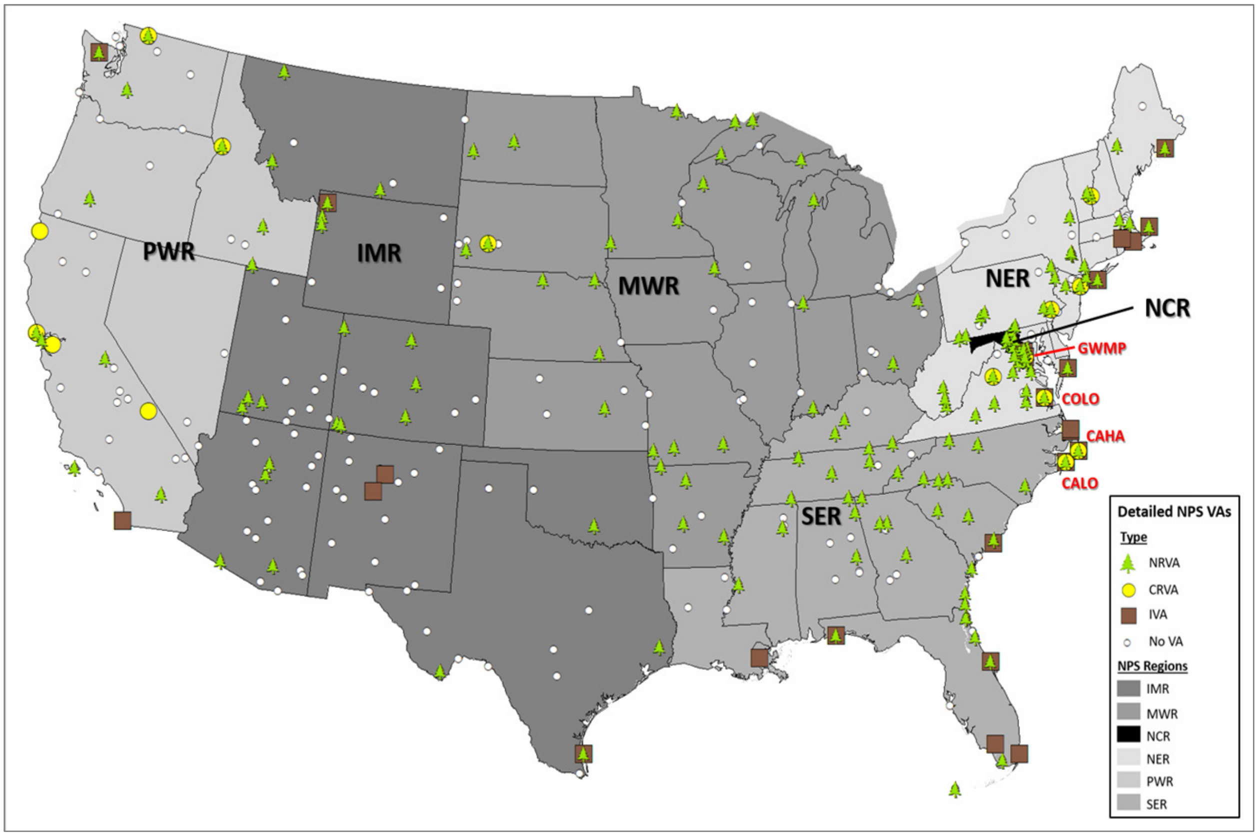

Figure 1-3. Geographic distribution of detailed NPS-specific studies included in all VA review chapters, within the contiguous U.S. Each VA symbol represents the centroid of any NPS unit included within the review, regardless of the quantity of VAs within the unit. Parks with all three VA types are labeled in red. NPS units lacking detailed VAs (within this review) are shown as white dots, and NPS regions are shown in shades of grey. Broad-scale (extent) studies are not included as detailed VAs.

[2] Subsequent to this study, many NCR parks received park-specific, landscape-focused VAs that specifically evaluated exposure, sensitivity, and adaptive capacity of parks (see Smyth et al. 2018).

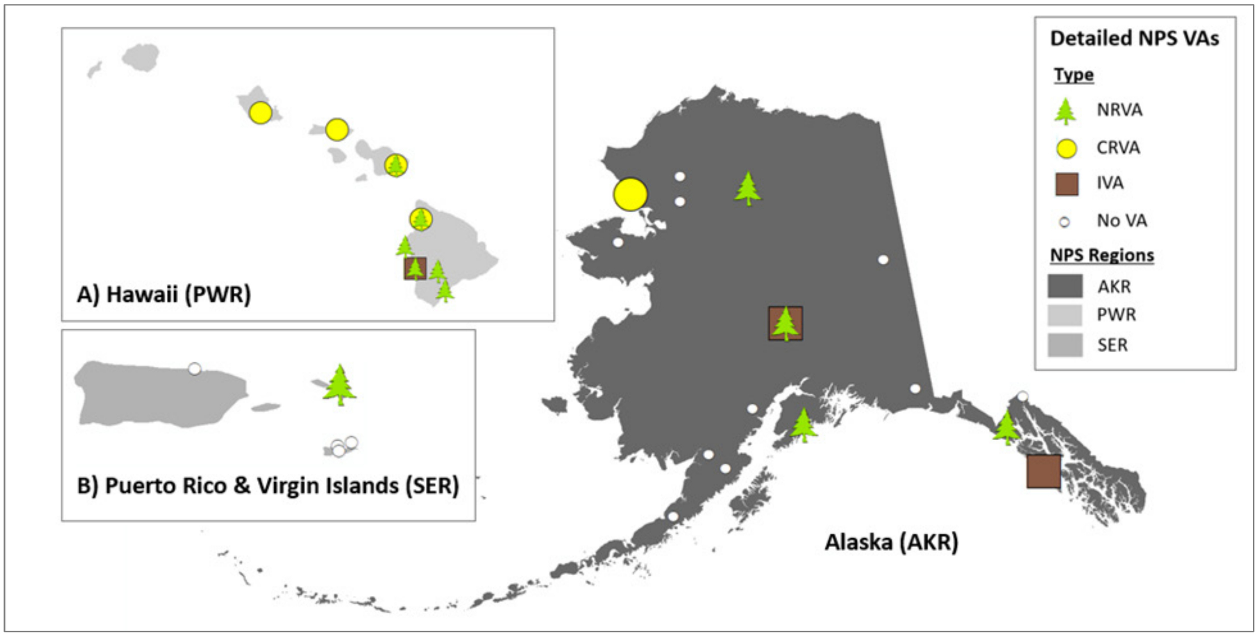

Figure 1-4. Geographic distribution of detailed NPS-specific studies included in all VA review chapters, within Alaska, Hawaii (inset A), and Puerto Rico and the Virgin Islands (inset B). Vulnerability assessments conducted in Guam and American Samoa are not shown. Each VA symbol represents the centroid of any NPS unit included within the review, regardless of the quantity of VAs within unit. NPS units lacking detailed VAs (within this review) are shown as white dots, and NPS regions are shown in shades of grey. Broad-scale (extent) studies are not included as detailed VAs.

The most striking result illustrated in Figure 1-3 is the relative absence of CRVA and IVAs across the entire NPS system. Through 2018 there were 169 NPS units with at least one detailed NRVA, 29 with IVAs, and approximately 20 with CRVAs (Figure 1-3, and Figure1-4). Only five NPS units at the time of this study were the focus of all three types of VAs (detailed IVA, NRVA, and CRVA). This includes two in the SER (CALO and CAHA), two in the NER (COLO and FIIS), and one in the NCR (GWMP). Several parks were the focus of more than one detailed IVA, NRVA, and/or CRVA (see review chapters for further information).

Most IVAs and CRVAs focus on coastal units, while the NRVAs are more evenly distributed across the NPS system (Figures 1-3, and 1-4). The concentration of VAs in the coastal parks is attributed to the current and anticipated impacts of SLR and storms associated with changing climate. In addition, compared to other climate change stressors (e.g., temperature and precipitation), SLR is relatively well understood and mapped, making vulnerability easier, quicker, and less expensive to assess. Other multi-hazard assessments have been challenged by lack of data.

1.10 Challenges and Lessons Learned

Park Capacity and Vulnerability Assessments

Only a very small portion of the park VAs evaluated in this volume include an NPS author, and even fewer were conducted or led by park staff. This low representation of NPS staff emphasizes the limited capacity of park staff to design, conduct, contract, and in some cases even participate in a VA. Parks rarely have the time or expertise needed to independently direct a VA, in part due to the huge variation in the focus, scale, scope, and resolution of VAs, and the myriad approaches and methods (Figure 1-1). Most parks need assistance identifying appropriate goals for a park-specific VA and most will benefit from outside advice on the design and conduct of a VA that best fits their resources, needs, and impending decisions.

Consistent Vulnerability Assessment Terminology and Protocols

A variety of terms are used inconsistently in this volume; chapter-specific definitions of common terms are included in the Glossary. Some terms have well-established, but different, discipline-specific definitions. During the conduct of this study, the NPS CCRP finalized a glossary (NPS 2021b) that addresses many issues of terminology and will contribute to more consistent use of terms.

Developing common protocols to achieve efficiencies will remain a challenging issue due to huge variations in park size, resources, capacities, priorities, and settings. The NPS developed a protocol and funded a series of SLR climate vulnerability studies that employ a consistent methodology, thereby achieving significant efficiencies (WCU and NPS 2016; see IVA chapter description). Other ongoing projects are focused on developing repeatable, efficient VA methods for cultural resources in western parks (CREVAT – Cultural Resources Environmental Assessment Tool; Hartfield et al. 2019) and in eastern park settings (Seekamp et al. 2019; Xiao et al. 2019). Similarly, opportunities exist to evaluate high-impact climate stressors, such as SLR and fire. However, the range of NPS resources, park settings, and unique situations ensures that a diversity of approaches will be necessary to meet NPS system-wide needs for VAs. Michalak et al. (2021) comprehensively evaluated priority needs for VAs and a broad range of potential strategies to efficiently meet high-priority needs.

Communication and Vulnerability Assessment Archiving

All collaborators reported difficulties identifying and acquiring park-specific VAs. A clear recommendation (see above) is to develop basic standards for VAs, including archiving all major VA products in NPS IRMA.

Considering Trade-Offs in Scope and Detail

A consistent trade-off across all disciplines is that of scope versus detail (Figure 3-3 in Chapter 3). General, or screening, assessments rarely provide the resource- or asset-specific data needed to support site-specific decisions or treatments, but they are useful for identifying potential hazards or vulnerabilities across a broad spatial extent. These broader studies are an important way for park managers to quickly obtain vulnerability information that can help target high priority resources or develop more park-specific assessments. Each chapter in this document includes examples of these broad-scale (extent) VAs (e.g., IVAs – Peek et al. 2015; NRVAs – Young et al. 2015; CRVAs – Wilson 2014), which calculate vulnerability metrics across multiple parks. However, general studies are rarely able to include potentially important local and regional information on either impacts or specific resources. Vulnerability assessments with a narrower focus can incorporate park- and site-specific data that inform park-level management decisions, but results may not be easily adapted or applicable elsewhere. Some parks have successfully undertaken park-wide, detailed VAs (e.g., Schuurman et al. 2019; Runyon et al. 2021). These require a sustained effort by park staff and partners, but have substantial advantages in their ability to help integrate responses across the diverse resources that every park needs to manage simultaneously.

Aligning Vulnerability Assessments to Park Needs

Vulnerability assessments are most effective when the results can directly inform an identified park need (e.g., vegetation or wildlife management; facilities maintenance or development plan), or the VA is an integral part of a broader park adaptation effort (e.g., scenario planning; Star et al. 2016; NPS 2021a). As a prerequisite, determining the specific purpose of the analysis and need for the results will prevent products from "sitting on a shelf," effectively wasting the investment in the work. To inform decisions, the level of detail and effort directed to a VA needs to match the information needs and capacity of park staff and decision-makers. In this review, the most useful VAs employed straightforward, understandable methods, and presented vulnerability results and supporting information in formats that could be easily incorporated into routine resource- or facility-specific management plans and documents.

1.11 Recommendations and Best Practices

Each review chapter identified best practices and/or recommendations specific to infrastructure, natural, or cultural resources. Below we highlight attributes that characterize the best VAs.

Ensure the Vulnerability Assessment Matches Needs

At the earliest stages of a VA design, consider the resources, spatial scale, and resolution that is needed to support park management needs. These needs may be more vaguely defined information goals for routine management plans (fire, vegetation, transportation, operations) or specific rehabilitation or development projects. The design of a VA should include the overarching framework (Figure 1-1), how the study will be implemented, and the eventual products. While adaptation options are not technically a part of VAs, obvious actions in response to vulnerabilities should be included in a final report and included in discussions between the study investigators and park staff. Vulnerability assessments are most effective when park staff are involved throughout the study, and when results are designed to support specific management decisions.

Clearly Define Vulnerability Assessment Study Parameters

Following from the previous recommendation, once decisions are confirmed on study design, these decisions should be clearly articulated. Vulnerability assessment documentation should define the scope (e.g., range of resources, assets, values considered), geographic scale, and resolution of data and results that will constitute the VA. The NPS can avoid confusion by clearly defining terms commonly used in VAs, recognizing that well-established, discipline-specific, and contradictory definitions will remain in use (the NPS CCRP Glossary directly addresses this need; NPS 2021b).

Prioritize Resources to be Thoroughly Assessed

Financial and staffing resources are often unavailable to conduct a comprehensive, park-wide detailed VA. An initial, relatively quick and inexpensive coarse filter VA may efficiently identify vulnerable resources that merit more immediate actions or detailed VAs. The experience of conducting a screening VA will also enhance the park staff's ability to understand climate threats, VAs, and climate change adaptation.

Evaluate All Components of Vulnerability

The most robust VAs identify and evaluate all relevant components of vulnerability. For those VAs that use the traditional framework (Figure 1-2), this will include exposure, sensitivity, and adaptive capacity for living resources. For adaptive capacity, assessments can often benefit by explicitly considering intrinsic and extrinsic elements (e.g., physical species traits versus landscape changes caused by humans; Beever et al. 2015). For IVAs and CRVAs focused on non-living resources, vulnerability is a function of exposure and sensitivity.

Address Uncertainty

All climate change-based VAs make assumptions about physical processes, societal actions and greenhouse gas emissions, and the consequences of climate changes. This uncertainty, or range of possibilities, will be explicitly addressed in robust VAs. Hoffman et al. (2014) summarize a variety of ways to address uncertainty in the context of VAs and climate change adaptation. NPS (2021a) has advocated the use of climate futures in climate change adaptation. Climate futures are projections of consequential climate variables for a specific place and time. These climate futures represent the range of plausible climate projections and are a basis for developing more detailed assessments of the consequences of climate changes (Star et al. 2016; Runyon et al. 2020; Lawrence et al. 2021).

Vulnerability assessments that adopt a hazard-risk framework usually estimate the probability, or likelihood, of a critical climate event and the resulting impacts or consequences. Probability can be difficult or impossible to quantify and many VAs have used expert elicitation to assess it qualitatively. Hazard assessments are typically focused on “pulse” or acute events, such as fire or flood, and they are usually designed to support actions that reduce risks from a specific hazard. Most climate change-based VAs, in contrast, are designed to inform and support climate change adaptation pathways that may encompass long periods and respond to gradual or “press” stresses (Romieu et al. 2010).

Identify Key Vulnerabilities

Key vulnerabilities are those that most threaten park conservation and management goals (Gross et al. 2014). The concept of key vulnerabilities includes knowing which resources or assets are of greatest concern due to their relative vulnerability, and how important those resources are to achieving agreed-upon park management goals. Criteria used to identify key vulnerabilities will vary and may include implications for multiple conservation goals, magnitude and timing of likely impacts, reversibility of impacts, and societal consequences.

Archive Vulnerability Assessment Products in NPS IRMA

Chapter authors consistently reported challenges locating NPS VAs and acquiring VA products. Results of VAs would be consistently discoverable by ensuring that final products of all NPS-commissioned studies are submitted and archived in the NPS IRMA Portal (https://irma.nps.gov/Portal/) and by using consistent keywords and other information management practices to facilitate discovery and bundling of VA products.

Embrace Partnerships
Most VAs require personnel to evaluate historical climate observations and future projections, evaluate park resources, identify climate threats, and lead a collaborative project. Relevant expertise may best be acquired from local resource experts, national programs fluent in evaluation of large climate datasets, and park staff that best understand a park's context, needs, priorities, and limitations. Many sources of information relevant to a VA originate and are managed outside of the NPS, emphasizing the benefit of working with partners familiar with sources of information and the skills to process it. Some planning approaches, such as "deep dive" scenario planning (Runyon et al. 2020), require considerable expertise in the planning process itself, and participants with sufficient knowledge of the resources and their relationships to climate drivers.

1.12 Concluding Remarks

A notable result of these studies is the relative lack of CRVAs or IVAs across the national park system. Although the NPS is actively working to address needs for VAs, methods to conduct CRVAs are now being actively developed, and considerable research is needed. In contrast, there are many established methods, and a diversity of approaches, for conducting NRVAs and IVAs.

Among the VAs examined, IVAs are most likely to be quantitative and conducted within a hazard-risk framework; quantitative assessments of probabilities (where possible) are often important, and in many cases necessary to meet engineering and/or regulatory requirements. Probabilities are particularly difficult to assign to many aspects of VAs of living resources because species interactions and adaptive responses are important (Ockendon et al. 2014) and difficult to forecast.

Vulnerability assessments of parks and park resources span a range of geographic scales, scope (breath of resources considered), and climate factors considered. The NPS has needs for a broad range of VAs, from relatively quick and inexpensive "coarse filter" studies that increase a park staff's understanding of climate changes and vulnerabilities, to comprehensive VAs that require teams with expertise in planning, park resources, and the methodology used to conduct the assessment. Results from this study will help the NPS design, conduct, and use VAs to address and adapt to challenges posed by climate change.

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Chapter 2: A Review of Vulnerability Assessments for National Park Service Infrastructure

Blair R. Tormey, Katie McDowell Peek, Holli L. Thompson, and Robert S. Young

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

Johnson Beach Road, Gulf Islands National Seashore. (©Program for the Study of Developed Shorelines, Western Carolina University)

Please cite this chapter as:

Tormey, B.R., K.M., Peek, H.L. Thompson, and R.S. Young. 2022. Chapter 2: A review of vulnerability assessments for NPS infrastructure. Pages 26-62 *in* Peek, K.M., B. R. Tormey, H.L. Thompson, A. C. Ellsworth, and C.H. Hoffman (editors). 2022. Climate change vulnerability assessments in the National Park Service: An integrated review for infrastructure, natural resources, and cultural resources. Natural Resource Report NPS/NRSS/CCRP/NRR—2022/2404. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/nrr- 2293650.

2.0 Executive Summary

This chapter review investigates vulnerability assessment approaches used to understand potential natural hazard and climate change impacts to infrastructure within the National Park Service, as well as other local, state, federal, and international government agencies. Common natural hazard and climate change factors evaluated within the various assessment studies include temperature, precipitation, sea-level rise, storm surge, flooding, landslides, wildfire, and extreme weather. This chapter summarizes a review of over 90 documents related to infrastructure vulnerability and discusses several of the most relevant analyses in more detail. It also provides recommendations emphasizing protocols and best practices most appropriate for the National Park Service.

In the documents reviewed, four approaches characterize infrastructure vulnerability assessments: 1) exposure assessments, 2) scenario planning studies, 3) risk assessments, and 4) indicator-based vulnerability assessments. These approaches represent the range of common evaluation methods.

Exposure assessments typically involve modeling and/or mapping of natural hazards (or climate change stressors) relative to the physical location of assets. Many studies conflate exposure analyses with vulnerability or risk, while others more accurately recognize that exposure is only one component of vulnerability. Although it is not equivalent to vulnerability, exposure may highlight potential vulnerability or risk, particularly when evaluating infrastructure on a larger scale (extent or resolution), or when no appropriate sensitivity data exist.

Scenario planning workshops and studies assist managers by informing decisions related to climate projections and scenarios of local change. As a tool to inform decisions under uncertain and uncontrollable conditions, scenario planning often includes an exposure assessment or an evaluation of probability.

Risk assessments commonly include an evaluation of both probability (likelihood or frequency) and impact (severity or consequence). These assessments differ from other vulnerability methods by factoring in the probability of the event, hazard, or stressor, and are often engineering-based. While hazard exposure mapping might be incorporated, risk assessments tend to be more quantitative than qualitative.

Indicator-based vulnerability assessments use a set of indicators to represent and evaluate vulnerability. In many cases, indicators are determined for three components of vulnerability: exposure, sensitivity, and adaptive capacity. Exposure is often evaluated by comparing the extent of a hazard or stressor to the location of a specific asset. Sensitivity (how the resource will fare when exposed) is also evaluated in a variety of different ways, including the use of expert opinion, and using indicators such as historical information, condition, design, materials, engineering, and access. Related to the adaptive capacity (ability to adjust or cope) of non-living assets such as infrastructure, there are inconsistencies in how organizations consider this third component of vulnerability. Some organizations define adaptive capacity for infrastructure as design features that affect the ability of the managing organization to protect the infrastructure (e.g., a structure designed to be moved). The National Park Service considers adaptive capacity to be an inherent trait of living resources, and that non-living assets (such as infrastructure) have no inherent adaptive capacity. Thus, within the

National Park Service, management actions and design features that protect infrastructure (such as moving a building) are considered part of climate change adaptation.

Developing and evaluating potential adaptation strategies after the completion of an infrastructure vulnerability assessment is common, and many studies suggest that adaptation is the desired outcome of any assessment of vulnerability (not just for infrastructure). Adaptation strategies for infrastructure can be proactive or reactive following an event that causes damage and can be implemented at a wide variety of scales (resolutions). The level of detail in evaluating adaptation strategies may range from general, qualitative analyses to asset-specific cost-benefit analyses, or model-based engineering assessments.

Scale plays a major role in determining the infrastructure vulnerability assessment approach and the specific methodologies used. The scale (resolution) of an infrastructure vulnerability assessment can be categorized in two ways: spatial scale and infrastructure scale. Spatial scale (e.g., site-specific, community, regional, park, or state level) is related to hazard-specific vulnerability and risk metrics including exposure and probability. Infrastructure scale (e.g., component, asset, or system level) is related to asset-specific vulnerability and risk metrics including sensitivity, adaptive capacity, and impact.

Some assessments evaluate the physical vulnerability of infrastructure, while others address vulnerability from a functional or economic perspective (particularly for sensitivity and adaptive capacity). Transportation assessments often address functionality, given the integrated dependencies of transportation networks. Economic factors (e.g., replacement value) are most often included as indicators for adaptive capacity.

There are a wide variety of vulnerability scoring methods within the infrastructure vulnerability assessments evaluated. Many studies are qualitative and do not assign a score, but instead include a general discussion of the hazards and impacts. Others score vulnerability semi-quantitatively, ranking assets on a simple low-moderate-high (or similar) scale. Quantitative studies often incorporate additional factors, such as probability, weighting of indicators, computer models, or engineering analyses.

The following is a set of best practices for conducting infrastructure vulnerability assessments for national parks:

- Assess Criticality – It is effective to score criticality (how essential the asset is) separately from the physical vulnerability of assets, either to narrow the quantity of assets to be evaluated, or to help prioritize adaptation strategies. A hybrid approach is recommended, where criticality is determined using quantitative (e.g., traffic data) and qualitative (e.g., stakeholder/expert opinion) data. When possible, discussions of criticality should include a range of park personnel, partners, and experts, particularly those with institutional knowledge of assets.
- Complete a Detailed Exposure Assessment – Exposure is the foundation of any infrastructure vulnerability assessment and thus should be based on the most accurate datasets available. If

an asset is not exposed to a natural hazard or climate change stressor, it is not meaningful to evaluate its sensitivity to (or potential impact from) that hazard.

- Evaluate Sensitivity – Sensitivity analyses often rely on indicators that represent or characterize how the asset will fare when exposed. For infrastructure, indicators related to the physical attributes of the asset (e.g., condition, construction/materials) are most useful. When quantitative sensitivity data is lacking, subject matter experts can evaluate and score each sensitivity indicator.
- Evaluate Probability and Identify Potential Scenarios – Including probability provides managers with the likelihood of an event, hazard, or stressor. Probability is not always easy to quantify, and therefore, it may be useful to assess it qualitatively, using expert opinion, workshops, or surveys. Analyzing multiple future scenarios, together with probability, can provide more informed adaptation strategies.
- Evaluate and Prioritize Adaptation Strategies – Considering adaptation strategies in park planning and decisions is a primary purpose of assessing infrastructure vulnerability. A thorough examination of management capacity (e.g., funding, policy, feasibility) to implement protective actions can help inform the selection of appropriate adaptation strategies. A best management practice is to evaluate these strategies in a team or workshop format, in collaboration with internal and external parties (e.g., park staff, partners, and subject matter experts).

2.1 Acknowledgments

We would like to acknowledge the following people: H. Wang, R.L. Beavers, A.C. Ellsworth, C. Hawkins-Hoffman, P.L. Yu, M. Rockman, J. Michalak, J.J. Lawler, S. Norton, and J. Gross. This work was funded and developed by the National Park Service Park Climate Change Response Program, in partnership with Western Carolina University, through a Task Agreement (P16AC01773) with the Southern Appalachian Cooperative Ecosystems Studies Unit (Cooperative Agreement P14AC00882).

2.2 Acronyms

DOT: Department of Transportation

FEMA: Federal Emergency Management Agency

FHWA: Federal Highway Administration (DOT)

FMSS: Facilities Management Systems Software (NPS)

FWS: U.S Fish and Wildlife Service

GIS: Geographic Information Systems

IPCC: Intergovernmental Panel on Climate Change

IVA: Infrastructure Vulnerability Assessment

NOAA: National Oceanic and Atmospheric Administration

NPS: National Park Service

SLR: Sea-Level Rise

VA: Vulnerability Assessment

VAST: Vulnerability Assessment Scoring Tool (FHWA)

2.3 NPS Region and Unit Codes

Region Codes

AKR: Alaska Region

IMR: Intermountain Region

MWR: Midwest Region

NCR: National Capital Region

NER: Northeast Region

PWR: Pacific West Region

SER: Southeast Region

Park Unit Codes

ASIS: Assateague Island National Seashore

CACO: Cape Cod National Seashore

CALO: Cape Lookout National Seashore

COLO: Colonial National Historical Park

DENA: Denali National Park & Preserve

PUHO: Pu`uhonua O Hōnaunau National Historic Park

YELL: Yellowstone National Park

2.4 Introduction

Preparing for, and adapting to, the impacts of natural hazards and climate change is a critical management issue for the National Park Service (NPS). Developing adaptation strategies and hazard preparedness plans requires an understanding of the vulnerability of park resources and assets. Thus, completion of a natural hazards and climate change vulnerability assessment (VA) is important for both short- and long-term planning in national parks. This is true for natural and cultural resources, as well as for the infrastructure (e.g., roads, parking lots, visitor centers) that provides access to these resources.

The concept of vulnerability applies to a variety of disciplines (e.g., health and safety, socioeconomics, natural resources), and therefore is defined and calculated in many ways. The Intergovernmental Panel on Climate Change (IPCC) provides a commonly cited definition for climate change vulnerability: "Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (IPCC 2007).

Numerous entities and institutions (Asam et al. 2015; FHWA 2012; Filosa et al. 2018; IPCC 2007; NOAA 2010) use this three-component definition of vulnerability (exposure, sensitivity, and adaptive capacity), as also discussed in detail within a multi-agency guidance document (Glick et al. 2011). Generally, exposure refers to the extent or degree to which a resource experiences climate change or natural hazards; sensitivity is how the resource will fare when exposed; and adaptive capacity is the ability of the resource to adjust or cope with the hazard or climate change impacts.

Many research sectors, including natural resources, cities and populations, and socio-economic systems, calculate vulnerability by evaluating exposure, sensitivity, and adaptive capacity (e.g., Balica et al. 2009; 2012; Frazier et al. 2014; Füssel and Klein 2006; Handayani et al. 2017; Havko et al. 2017; Jurgilevich et al. 2017; Metzger et al. 2005; Polsky et al. 2007; Tapia et al. 2017; Yoo et al. 2011). However, this approach is less common in the built environment, and few infrastructure-specific studies calculate vulnerability explicitly using these three components/metrics. This is especially true within the NPS (described later in this chapter).

The NPS manages over 75,000 infrastructure assets (NPS 2017b); natural hazards and climate change already affect many of these assets. Understanding the vulnerability and risk to these assets is fundamental for prioritizing adaptation options and mitigating future damage to infrastructure and resources, as well as limiting disruptions in park operations.

Purpose and Scope

This review investigates different VA approaches for understanding potential natural hazard and climate change impacts to infrastructure. These studies include infrastructure vulnerability assessment (IVA) approaches used within the NPS, as well as other local, state, federal, and international government agencies. Common natural hazard and climate change factors evaluated within these IVA studies include temperature, precipitation, sea-level rise (SLR), storm surge, flooding, landslides, wildfire, and extreme weather. This report discusses a selection of the most relevant (i.e., focused on the physical vulnerability of infrastructure) of the over 90 infrastructure-related vulnerability documents reviewed (Appendix A). Figure 2-1 shows the geographic distribution of all reviewed IVAs within the U.S., as well as the distribution and quantity of NPS-specific IVAs.

This report summarizes and compares the four IVA approaches, highlights examples, and provides recommendations for best practices in assessing the climate change and natural hazards vulnerability of infrastructure, with an emphasis on protocols most appropriate for the NPS.

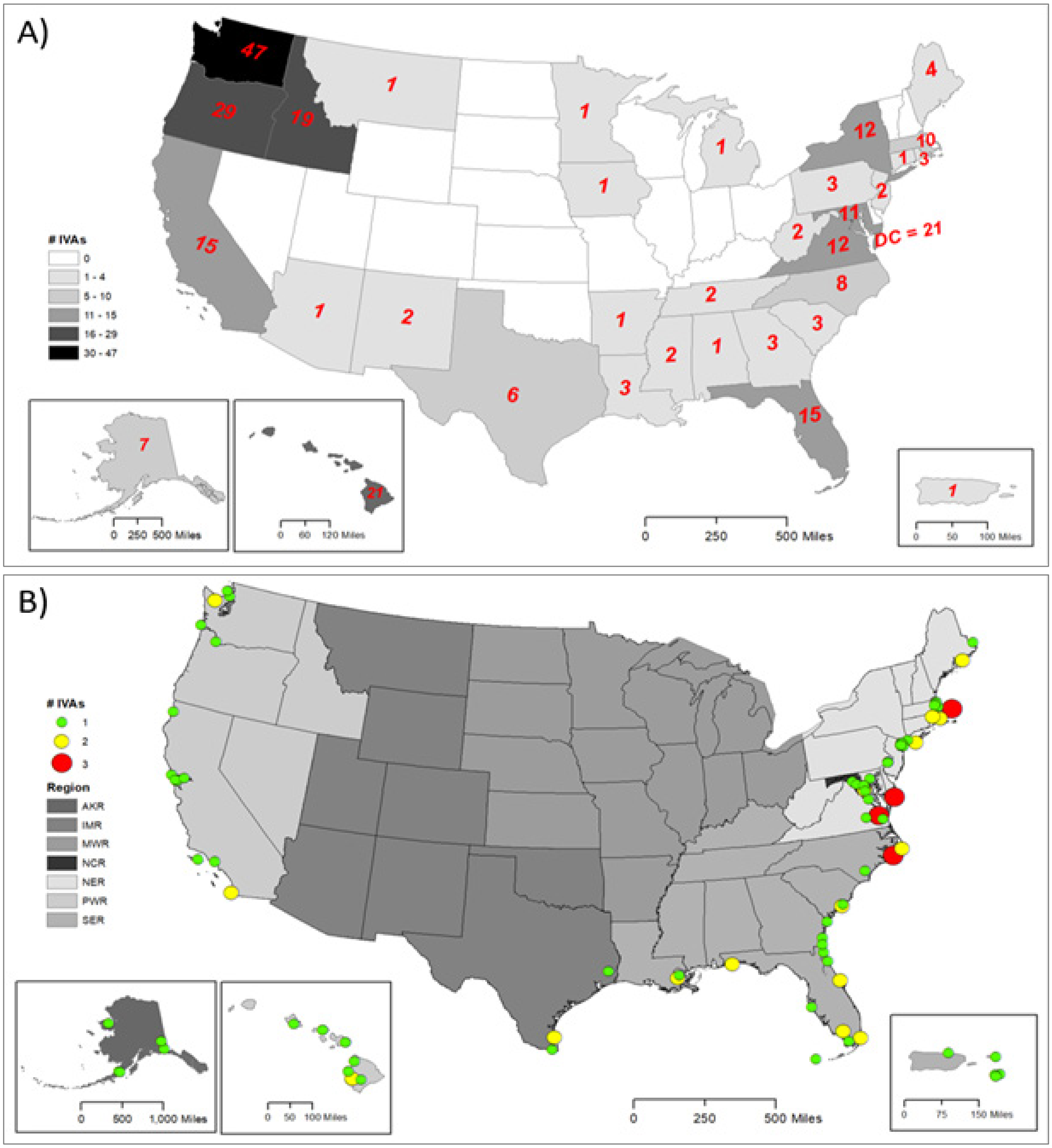

Figure 2-1. A) Geographic distribution (by state) of evaluated IVAs in the U.S. The red number indicates the specific number of IVAs from each state. The total number of IVAs in this figure does not equal the number of evaluated documents, as each document does not necessarily describe a single IVA. B) Geographic distribution and quantity of NPS-specific IVAs. Each dot represents the centroid of the NPS unit. One nationwide NPS assessment (that did not focus specifically on infrastructure) was not mapped (Monahan and Fisichelli 2014). International studies and those from Guam and American Samoa are not shown.

2.5 Results

In this chapter review, the term vulnerability encompasses efforts to characterize the impact of hazards and climate change on infrastructure. Four approaches characterize these infrastructure IVAs: 1) exposure assessments, 2) scenario planning studies, 3) risk assessments, and 4) indicator-based VAs. Not all studies fit neatly into a category. Instead, these categories represent the range of approaches (evident in the literature) to evaluate the vulnerability of infrastructure to natural hazards or climate change (Table 2-1). The following sections describe each of these approaches.

Table 2-1. Summary and common characteristics of IVA approaches.

IVA Approach	Method	Characteristics
Exposure Assessments	Involves modeling or mapping of hazards/stressors	Mapped hazard/stressor often compared to location of assets. Commonly first step of any IVA approach.
Scenario Planning	Involves examining & planning for a variety of futures (including climate projections)	Commonly includes an exposure assessment of hazards. More of a planning exercise, but includes elements of an IVA.
Risk Assessments	Involves evaluation of probability (likelihood) & impact (consequence)	Typically, quantitative & engineering- or model-based. "Impact" includes elements of exposure & sensitivity.
Indicator-based VAs	Uses a set of indicators to represent & evaluate vulnerability	Indicators often determined for metrics of vulnerability (exposure, sensitivity, adaptive capacity). Typically includes more detailed information about individual assets.

Exposure Assessments

Evaluating exposure is one of the most common approaches used to address natural hazards and climate change vulnerability for infrastructure. For infrastructure, the term exposure commonly refers to whether an asset is located in an area that experiences the hazard or impacts of climate change. **Many studies conflate the term by referring to exposure analyses as vulnerability or risk, while others more accurately recognize that exposure is only one component of vulnerability.** In some cases, however, exposure may highlight potential vulnerability or risk, particularly when evaluating infrastructure on a larger scale (not-asset specific, lower resolution) or when no appropriate sensitivity/impact data exists (e.g., MDOT et al. 2014; Winguth et al. 2015).

Exposure assessments typically involve modeling and/or mapping of natural hazards (or climate change stressors). The mapped hazard or stressor is compared to the physical location of assets, especially when the resolution of the study is asset specific. For example, many IVAs use Geographic Information Systems (GIS) to map road corridors or buildings that may be affected by natural hazards and climate change (e.g., MassDOT 2016; Peek et al. 2015a; in press; RK&K 2016). Even studies that utilize different IVA approaches (e.g., scenario planning or indicator-based VAs) usually include exposure assessments as a basic component (e.g., Jamie Caplan Consulting 2015;

NPS 2017a; Place Matters 2011; WCU and NPS 2016), as understanding the exposure of a resource is inherently the first step in understanding its overall vulnerability.

The NPS has conducted only a few (discoverable) natural hazard or climate change infrastructure exposure studies. Monahan and Fisichelli (2014) conducted a landscape-scale (resolution) exposure assessment of climate change stressors in national parks. This study did not evaluate specific infrastructure, but assessed the exposure of entire parks to changes in climate variables related to temperature, precipitation, frost and wet day frequencies, etc. The NPS published an exposure study in 2015, which evaluated the long-term SLR exposure of assets within 40 coastal national parks (Peek et al. 2015a). While this study is asset-specific, it is still relatively broad and intended only to provide an overall look at the SLR exposure of the NPS; it is not meant for decision-making at the unit or asset level.

In 2013, the NPS and University of Rhode Island researchers assessed the SLR and storm surge exposure of selected natural, cultural, and infrastructure resources within two national seashores (Murdukhayeva et al. 2013). These hazards were modeled and compared to the location and elevation of the parks. The probability of inundation was calculated for each model scenario (exposure) to determine the likelihood of each hazard.

The U.S. Department of Transportation (DOT) and Federal Highway Administration (FHWA) completed a significant number of studies in recent years on the exposure of transportation assets to climate change. Most of this work was part of the FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework (FHWA 2012; Filosa et al. 2018) and pilot resilience case studies (FHWA 2017a). Although this framework fits within the indicator-based VA protocol (see the indicator-based VA descriptions and discussion), in practice, data limitations forced many of these pilot projects to focus on exposure only (as opposed to vulnerability).

One of these pilot projects in Michigan (MDOT et al. 2014) evaluated the exposure of transportation assets (roads, bridges, culverts, and drainage infrastructure) to extreme precipitation and heat. Spatial analyses (GIS-based) helped to determine the exposure of each asset to various stressors under different climate projections according to future emissions scenarios. Because this study was part of the FHWA vulnerability framework (FHWA 2012), the authors acknowledged that vulnerability also includes sensitivity and adaptive capacity. However, due to the lack of data for these metrics, exposure was used to represent vulnerability; this was a common approach within the FHWA case studies (e.g., MassDOT 2016; MDOT et al. 2014; Winguth et al. 2015). The FHWA case study from Massachusetts used exposure as a proxy for vulnerability and determined that all assets analyzed (components of a highway system) have very high sensitivities and very low adaptive capacities (MassDOT 2016).

Municipal-level studies have also examined natural hazards or climate change exposure of infrastructure. A study in Queen Anne's County, Maryland, evaluated the infrastructure vulnerability (exposure) to coastal flooding and SLR (RK&K 2016). Three flooding conditions were mapped (2050 SLR, 2100 SLR, 2050 SLR plus storm surge), and compared to the location of public infrastructure in the county. The findings of this study were reported as vulnerability (not exposure);

however, the authors noted that the results were based on the infrastructure footprint and did not include information such as the finished floor elevations (which is often part of sensitivity).

Scenario Planning Studies

Scenario planning for infrastructure vulnerability involves examining and planning for a variety of possible futures (Appendix B—e.g., Andrew et al. 2015; Ecosystem Management 2014a; b; Lee et al. 2015; Place Matters 2011; Rasmussen et al. 2012; 2015; Simmons et al. 2015; U.S. DOT Volpe Center 2011a; b; 2013). This can involve considering hazards of different magnitudes (e.g., moderate versus extreme storm surge from a hurricane) or differing rates of change in stressors over time (emissions, SLR, etc.). In addition, scenario planning for infrastructure may examine the range of responses that a vulnerable system might have to a single climate change or natural hazard factor (e.g., population growth, transportation networks, or land use scenarios in response to a 1-foot SLR).

Scenario planning is used to help managers make decisions using climate change projections and scenarios of local change. It can be a powerful tool when the range of outcomes vary depending on changing conditions over time or for those climate change stressors where the direction of change may be uncertain (i.e., will precipitation increase or decrease; Anderson et al. 2015a; b; GHD 2014; Rasmussen et al. 2015). Scenario planning is not necessarily an IVA protocol, but it often includes an exposure assessment or an evaluation of probability. It is included here as a separate approach because many organizations use this process for adaptation planning, which commonly begins with an assessment of vulnerability.

The U.S. DOT Volpe Center worked with state, regional, and federal stakeholders (including the FHWA, NPS, U.S. Fish and Wildlife Service [FWS], Environmental Protection Agency, National Oceanic and Atmospheric Administration [NOAA], Federal Emergency Management Agency [FEMA], Department of Defense, Cape Cod Commission, CACO, and Cape Cod Regional Transit Authority) on a scenario planning project on Cape Cod, Massachusetts, which integrated climate change into existing and continuing transportation, land use, coastal zone, and hazard mitigation planning processes (Place Matters 2011; Rasmussen et al. 2012; U.S. DOT Volpe Center 2011a). The project applied a GIS-based software tool to develop transportation and land use scenarios in areas vulnerable (exposed) to climate change impacts, such as SLR, erosion, and storm-related events.

In central New Mexico, the Volpe Center again worked with multiple agencies (including the FHWA, FWS, NPS, Bureau of Land Management, and the Mid-Region Council of Governments) to assist transportation and land use decision-making in the Albuquerque region through scenario planning (Andrew et al. 2015; Ecosystem Management 2014a; b; Lee et al. 2015; Rasmussen et al. 2015; Simmons et al. 2015). The scenario planning process considered data related to several climate change factors (flooding, drought, temperature change, wildfires, and extreme weather). The study also evaluated how the central New Mexico region could develop in a way that minimizes greenhouse gas emissions and increases resiliency to climate change (through minimizing the development footprint, wildfire risk, flood risk, and impacts to crucial wildlife habitat).

Risk Assessments

Risk assessments are a common approach for using VA data and thereby addressing climate change and natural hazards to infrastructure (Appendix C—e.g., Brooks and Clark 2015; Canadian Council of Professional Engineers 2008; Felio 2015; Genivar Consultants 2010; HES 2017). Risk is most often evaluated as a combination of probability (likelihood or frequency) and impact (severity or consequence). Risk differs from vulnerability (as defined in IPCC 2007) through considering the probability of the event, hazard, or stressor, and for infrastructure, risk assessments are often engineering-based (e.g., Armstrong et al. 2016; Canadian Council of Professional Engineers 2008). While hazard mapping (exposure) might be incorporated, risk assessments tend to be more quantitative than qualitative, largely due to the calculation of probability and the inclusion of engineering analyses.

In 2016, the NPS worked with the FHWA on a risk assessment for Denali Park Road (in DENA), a 92-mile corridor that provides the only access to the park and preserve (NPS 2016). The risk assessment included geohazards mapping (distribution, susceptibility, and probability of landslides and permafrost subsidence), and analyses/recommendations with respect to other risks to the road (alteration of facility assets/standards, revised vehicle specifications, changes in maintenance, operations, and park management) for incorporation into the park's transportation plan. In 2017, this risk assessment process expanded to all of Alaska as part of the state's long-range transportation plan (NPS 2017a). As of the writing of this report, the NPS was also conducting risk assessments at multiple parks in partnership with the National Renewable Energy Laboratory.

Risk assessments can also apply to historic properties and infrastructure. For example, Historic Environment Scotland conducted a climate change risk assessment of historic sites, including infrastructure (HES 2017). The GIS-based spatial analysis focused on the likelihood of fluvial flooding, pluvial flooding, coastal flooding, coastal erosion, groundwater flooding, and slope instability. The impact of each hazard was scored using expert opinion regarding the potential damage to the infrastructure and corresponding site.

Finally, as described in a series of reports (Canadian Council of Professional Engineers 2008; Felio 2015; Genivar Consultants 2010), the Canadian Government conducted an engineering risk assessment of public infrastructure. The assessment focused on four infrastructure categories: stormwater and wastewater, water resources, roads and associated structures, and buildings. Vulnerability (risk) was rated qualitatively using professional judgment. This protocol used a probability and severity scale to calculate the priority of the effect of climate change factors on each building component (0 to 7 scale). From these two scales, a total "priority of climate change affect" was calculated.

Indicator-Based Vulnerability Assessments

Indicator-based VAs use a set of indicators to represent and evaluate vulnerability, often developing indicators for three components/metrics of vulnerability: exposure, sensitivity, and adaptive capacity (Appendix D—e.g., Almodovar-Rosario and Dorney 2014; Cambridge Systematics 2015; City of Carlsbad 2017; DeFlorio et al. 2014; Dorney et al. 2015; Filosa et al. 2018; ICF International 2012a; b; 2014a; 2017; Maryland State Highway Administration and Santec Consulting Services 2014; San

Francisco BCDC and MTC 2011). Indicator-based VAs can be qualitative or quantitative (or both), although in most cases the resulting vulnerability is reported on a semi-quantitative scale (e.g., low, moderate, high). These assessments often focus on one or two timeframes (e.g., to the year 2050 or 2100), and use a variety of methods and indicators to evaluate the three components (Table 2-2).

Exposure (whether the resource of interest is in an area that does or will experience the hazard or impacts of climate change) is often evaluated by comparing the extent of a hazard or stressor (e.g., potential SLR flooding) to the location of a specific asset. Regionally downscaled climate data from global models provide projections of climate stressors, particularly temperature and precipitation (e.g., Anderson et al. 2015a; b; Armstrong et al. 2016; Choate et al. 2017; ICF International 2013b; 2017; ODOT 2014; Simmons et al. 2015; SSFM International 2011). Sensitivity (how the resource will fare when exposed) and adaptive capacity (the ability of the resource to adjust or cope with the hazard or climate change impacts) are also evaluated in a variety of ways, including the use of expert opinion, and considering indicators such as historical information, condition, design, materials, engineering, and access.

Table 2-2. Summary and key characteristics of select indicator-based VA studies.

Indicator-based VA	Hazards/Stressors	Exposure Indicators	Sensitivity Indicators	Adaptive Capacity Indicators
FHWA San Francisco Case Study (San Francisco BCDC & MTC 2011)	SLR & seismicity	Depth of SLR inundation for two time periods	Level of use, age of facility, seismic retrofit status, maintenance cost, liquefaction susceptibility	Availability of a comparable asset (with similar functionality, redundancy)
NPS Facilities Adaptation in Coastal Areas (ICF International 2012b).	Coastal hazards (SLR & storm-related coastal inundation & erosion)	Dune protection, elevation, breach points, presence of vegetation	From NPS facilities database: facilities condition index	From NPS facilities database: current replacement value
FHWA Gulf Coast Study (ICF International 2014a)	Temperature, precipitation, SLR, storm surge, & wind	# of days > 95°, 1% annual likelihood rain event, SLR inundation scenarios, surge inundation depth, wind threshold exceedance	Varied by stressor & asset type. For highways & SLR: past flooding, protective engineering, approach elevation of bridges	Varied by asset type. For highways: replacement cost, redundancy, duration of operational disruption
FHWA Central Texas Case Study (Cambridge Systematics 2015)	Flooding, drought, extreme heat, wildfire, & others	Modeled freeboard, vertical proximity to floodplain, or past exposure; projected change soil moisture & dry days/year; projected change # days ≥ 100° F & average 7-day max temp	Varied by stressor & asset type. For highways & extreme heat: pavement binder & truck traffic volume	Varied by asset type. For railways: asset criticality & average daily ridership
NPS Coastal Hazard & SLR Protocol, with WCU (WCU and NPS 2016)	Coastal hazards & SLR	Flooding potential (100-yr floodplain), modeled surge & SLR inundation, erosion potential, historical flooding/erosion	Flood damage potential (elevated), storm resistance, asset condition, historical damage, protective engineering	Not evaluated or included in vulnerability score
City of Carlsbad (2017)	SLR & coastal hazards	Modeled flooding, shoreline change, & bluff response to 100-yr wave event	Expert opinion on potential damage & service interruption	Expert opinion on effort needed to adapt/ability to adapt
FWS Extreme Weather Infrastructure Study (ICF International 2017)	Precipitation/flooding, SLR, wildfire, landslide, & extreme heat	Flooding potential (500-yr floodplain), projected land category/SLR inundation, wildfire potential, landslide hazards, projected % change in 90th % temp	From FWS facilities database: condition, remaining service life, & asset material	From FWS facilities database: historic status, current replacement value; for roads/trails: class (type of road) & length

Federal Highway Administration Studies

The FHWA (U.S. DOT) has conducted numerous indicator-based VA studies. Between 2008 and 2015, the FHWA completed the Gulf Coast Study (Table 2-2), which assessed the vulnerability of transportation infrastructure to climate change factors such as SLR, storm surge, temperature change, and wind (CCSP 2008; ICF International 2013b; 2014a; b; ICF International and PB Americas 2011; Parsons Brinckerhoff and ICF International 2014). This project focused on transportation systems in Mobile, Alabama, using an indicator-based VA in which vulnerability is calculated as a combination of the three components (exposure, sensitivity, and adaptive capacity). A single exposure indicator was used for each climate change stressor (independent of the transportation type). For example, the exposure indicator for SLR examined whether an asset was inundated under specific model scenarios. The assessment of sensitivity evaluated a variety of indicators specific to the asset type (roads, bridges, etc.) and stressor (SLR, storm surge, temperature change, etc.). Adaptive capacity indicators were unique to the transportation asset type but not specific to the stressor. For example, the ability of managers to quickly repair damage was an adaptive capacity indicator of highways among all climate change stressors. In addition to calculating vulnerability, evaluating criticality and potential adaptation measures were key aspects of this study.

In 2010, the FHWA began a series of pilot studies based on a conceptual framework for assessing the climate change vulnerability and risk of transportation infrastructure (FHWA 2017b). A revised VA framework resulted from these pilot studies (FHWA 2012) which served as the basis for additional climate change/extreme weather resilience and vulnerability pilot studies. The 2012 VA framework was further updated in 2018 (Filosa et al. 2018) and included the following strategies: developing an inventory of assets, evaluating the significance and priority of assets, identifying and gathering climate data, assessing vulnerability and considering risk, identifying adaptation options, and integrating vulnerability into decision making. Like the previous Gulf Coast Study (ICF International 2014a) and the 2010 and 2012 FHWA protocols, the 2018 revised framework emphasized use of an indicator-based VA in which vulnerability was calculated as a combination of exposure, sensitivity, and adaptive capacity.

Subsequently, an additional 19 state- and local-level case studies were completed that focused on climate change and extreme weather vulnerability and adaptation options of transportation systems. One case study from Hillsborough County, Florida, involved a wide range of partners, stakeholders, and consultants, including Florida DOT, public works departments, planning councils, and universities (DeFlorio et al. 2014). This case study had three primary phases, the first of which was focused on the asset inventory, criticality, and hazard vulnerability/risk. Hazards analyzed included SLR, storm surge, and inland flooding, evaluated to the year 2040. Models were used to determine exposure for each hazard, including a Florida-specific SLR model, NOAA's Sea, Lakes, and Overland Surges from Hurricanes model (SLOSH; NOAA NHC 2018), and FEMA flood maps (FEMA 2017). Sensitivity was evaluated qualitatively by determining the approximate number of weeks that functionality would be lost (no specific scores were given for this metric). Adaptive capacity was assessed using a planning model that measures reduced systems functionality (using vehicle miles traveled, delay, and lost trips) when a roadway or transportation asset was disabled.

After evaluating these metrics, the planning team also examined potential impacts to regional mobility and economics, as well as adaptation strategies.

Within an indicator-based VA, exposure indicators usually consist of data from climate change or hazard models, occasionally including historical data as well. Scoring sensitivity and adaptive capacity is more challenging. Numerous asset attributes and characteristics could influence sensitivity and adaptive capacity, which makes it hard to assign indicators for these metrics. To help with this issue, the FHWA created an Excel-based tool, called the Vulnerability Assessment Scoring Tool (VAST) to identify potential indicators (FHWA 2018). The VAST includes a large indicator library for both sensitivity and adaptive capacity that is specific to different climate change factors and natural hazards. In addition to this library, the VAST guides the user through scoring the exposure, sensitivity, adaptive capacity, and vulnerability of transportation infrastructure.

A FHWA case study from central Texas applied the VAST to calculate the vulnerability of transportation assets (roadways, bridges, rails) to flooding, drought, extreme heat, wildfire, and extreme cold to the year 2040 (Cambridge Systematics 2015), scoring exposure, sensitivity, adaptive capacity, and vulnerability of the 10 most critical assets. Indicators were chosen for each metric and hazard combination (the VAST only suggests potential indicators, as the user must then decide which are appropriate). For example, flooding exposure was evaluated as a combination of 1) modeled available freeboard, 2) vertical proximity to the 100-year floodplain, and 3) past exposure (anecdotal). Sensitivity indicators for flooding included: 24-hour precipitation design threshold, scour critical status (for bridges), average inundation velocity associated with rain event, and wildfire threat. Adaptive capacity was evaluated specific to the asset type (not the hazard); for highways, adaptive capacity indicators included asset criticality, functional classification, daily traffic, and detour length. Using asset criticality within the adaptive capacity scores is less common, as it assumes that if an asset is more critical, it is also less adaptive.

<u>NPS Studies</u>

There have been a limited number of NPS infrastructure-specific climate change or natural hazard VAs, the majority of which have been indicator-based VAs. In 2012, the NPS began a pilot indicator-based VA study that focused on two coastal national parks, ASIS (ICF International 2012a; 2013a) and PUHO (ICF International 2012b). Like the FHWA projects, this study calculated vulnerability as a combination of exposure, sensitivity, and adaptive capacity. Exposure was calculated by assessing site-specific characteristics related to the coastal hazards being analyzed (i.e., elevation, vegetation, soil erosion, dune presence); sensitivity and adaptive capacity were calculated using attributes obtained directly from the NPS facilities database (Facility Management Software System; FMSS). The asset's facilities condition index (which relates to the asset's deferred maintenance) was used for sensitivity, and the current replacement value for adaptive capacity (Table 2-2).

Beginning in 2015, the NPS partnered with the Program for the Study of Developed Shorelines at Western Carolina University to create a Coastal Hazards and SLR Asset Vulnerability Assessment Protocol (WCU and NPS 2016). The focus of this indicator-based VA protocol was to assess the vulnerability of buildings and transportation assets within coastal national parks to the year 2050. Vulnerability was evaluated as a combination of exposure and sensitivity; adaptive capacity was not evaluated or included in the final vulnerability score (Table 2-2). This protocol standardized the methodology and data for assessing vulnerability of coastal infrastructure. Exposure indicators for this coastal hazard protocol included flooding potential, extreme event flooding (e.g., storm surge, tsunamis), SLR, shoreline change, and historical/reported coastal hazards. Sensitivity indicators in this protocol were not from an existing database, but instead considered the physical characteristics of an asset itself, including flood damage potential (e.g., is it elevated), storm resistance, asset condition, historical damage, and protective engineering. The primary data source for much of the sensitivity analysis was an asset-specific questionnaire completed by park staff. As of 2018, this protocol has been applied at approximately 20 coastal parks (e.g., Peek et al. 2015b; c; d; e; 2017a; b; c; d; e; f; g; h; i; j; k; l; 2018; Tormey et al. 2018a; b; WCU and NPS 2016). Several follow-up climate change adaptation projects within the NPS used results of this indicator-based VA protocol, including research conducted by the University of Rhode Island at COLO (Ricci et al. 2019a; b) and CALO (Fatorić and Seekamp 2017).

U.S. Fish and Wildlife Service Study

The Pacific Region Constructed Asset Climate Change Vulnerability Tool was created to help the FWS screen for infrastructure vulnerability to SLR, inland flooding, extreme heat, wildfire, and landslides (ICF International 2017). This tool focused on assets within FWS Pacific Region Refuges and Hatcheries, with more specific workshops at six individual units. This protocol calculated vulnerability as a combination of all three metrics, and sensitivity and adaptive capacity indicators were obtained from existing data within the FWS facilities management database (Table 2-2). Sensitivity was scored using a combination of attributes from the database, including the facilities condition index (buildings) or pavement condition rating (roads), remaining service life (approximate years of service life left), and asset material. Adaptive capacity was scored as a combination of historic status, current replacement value, and road/trail class and length.

Municipal Studies

Municipalities have also used indicator-based VAs for infrastructure (e.g., City of Carlsbad 2017; City of Everett 2018; Havko et al. 2017). The City of Carlsbad, California completed a coastal hazard VA for numerous resources and assets, including beaches, public access ways, parcels, critical infrastructure, transportation infrastructure, and environmentally sensitive lands (City of Carlsbad 2017). Coastal hazards were analyzed to the years 2050 and 2100, and included landward beach migration, bluff erosion, and flood inundation related to change in sea level. Numerical scores were assigned for exposure, sensitivity, and adaptive capacity for each asset category based on a rating system and expert opinion; these scores were combined to give an overall vulnerability score. The authors of this study recognized that the built environment does not adapt naturally, and therefore inherently has a low adaptive capacity. Potential adaptation strategies were evaluated, including secondary impacts and trade-offs (i.e., who benefits and who is adversely impacted).

The City of Everett, Washington implemented a slightly different approach that evaluated the vulnerability of resources to various factors, including earthquakes, severe storms, climate change, fire, flooding, hazardous materials, landslides, tsunami, and volcanic eruptions (City of Everett 2018). Resources of interest for this study included the general population, property, critical facilities, and infrastructure. This indicator-based VA first calculated exposure by comparing hazard data with asset locations using GIS. Vulnerability was then evaluated by interpreting potential weaknesses or problems of the exposed resources. Risk was also determined by describing the most probable scenario and impact for each hazard.

2.6 Discussion

It was difficult to separate the identified IVA approaches into four distinct categories, as they have many common characteristics and challenges (Table 2-1). An exposure assessment is the first step to an indicator-based VA and is often the first step during scenario planning. Similarly, risk assessments include the impact of a hazard or stressor, which includes elements of evaluating exposure and sensitivity within an indicator-based VA. The Australian Capital Territory protocol (AECOM 2010; 2012), for instance, is a hybrid of risk analysis and an indicator-based VA, where vulnerability is defined as a function of risk (exposure, generic sensitivity, and risk-specific sensitivity) and adaptive capacity (generic and risk specific).

Much of the overlap of the four identified IVA approaches is due to terminology, as the terms exposure, vulnerability, and risk are often used interchangeably. The term resilience is also widely used when discussing natural hazards or climate change vulnerability and adaptation. The FHWA published several reports on assessing the resilience of transportation assets to climate change and extreme weather (e.g., Choate et al. 2017; ten Sietfhoff et al. 2017). Although these studies use climate resilience as an overarching theme, vulnerability (and adaptation) remains the primary focus of each assessment.

Common Approach Themes

<u>Assessing Criticality</u>

The evaluation of criticality (how essential the asset is) is a common process within all four IVA approaches, particularly within indicator-based VAs (e.g., Cambridge Systematics 2015; DeFlorio et al. 2014; GHD 2014; Hogan et al. 2014; ICF International and PB Americas 2011; Merrill and Gates 2014; NJTPA 2011; ODOT 2014; WSDOT 2011). Agencies (including the NPS) and municipalities often have hundreds or thousands of infrastructure assets; assessing the criticality of these assets prior to an IVA helps prioritize which should be evaluated for maximum efficiency. Criticality can also be addressed after an assessment is complete, to prioritize adaptation strategies for infrastructure with high vulnerability. In many IVAs, criticality is part of the vulnerability formula (e.g., vulnerability = criticality X potential impact; GHD 2014) or used as one indicator for the adaptive capacity of an asset (e.g., Cambridge Systematics 2015).

Using quantitative methods to determine criticality can be time- and resource-intensive, therefore many analyses use qualitative methods (e.g., expert opinion, *see* Cambridge Systematics 2015). Many of the FHWA case studies include criticality (e.g., Abkowitz et al. 2015; Cambridge Systematics 2015; Hogan et al. 2014; ICF International 2011; ICF International and PB Americas 2011; Merrill and Gates 2014; ODOT 2014). The FHWA also released a guidance document (ICF International 2011) summarizing three approaches for assessing the criticality of transportation assets: 1) a desk review, which uses quantitative methods and available data sources (e.g., daily traffic, evacuation routes and access to hospitals, functional classification), 2) stakeholder elicitation, which uses local expert opinion, and 3) a hybrid approach, which uses a combination of the desk review and the stakeholder elicitation.

Criticality often includes criteria focused on social, operational/functional, and economic importance. In many cases, criticality focused on the consequences of removing an asset from service. This was the case in the 2014 FHWA MDOT study, where the criticality of bridges was calculated by the following factors: traffic volume, functional classification, detour length, cost of replacement, and economic impact (MDOT et al. 2014). Another FHWA example is from the NJTPA (2011); criticality was assessed for transportation assets using: the importance of the destination (based on jobs and population density), the magnitude of connections (based on traffic volume), and emergency functions of the routes (based primarily on the presence of coastal evacuation routes).

Many agencies (including the NPS) maintain a facilities management database that includes attributes related to criticality. The NPS database (FMSS) contains an attribute called asset priority index (NPS 2018), which ranks the significance of each asset in terms of the park mission and uniqueness (i.e., whether a comparable substitute exists). This type of database can be useful for quickly evaluating criticality, and/or to filter and manage large quantities of asset data.

In many studies, criticality is included indirectly. These studies focus on only a few critical assets, chosen with prior knowledge of the significance of the infrastructure (e.g., Canadian Council of Professional Engineers 2008; Dorney et al. 2015; Havko et al. 2017; Jamie Caplan Consulting 2015; Murdukhayeva et al. 2013). These studies do not evaluate criticality specifically; instead, criticality is inherently addressed when defining the project scope (e.g., deciding to only evaluate the highest priority assets such as interstates within a road network). By choosing to only evaluate the vulnerability of a limited number of high priority assets, these studies indirectly include criticality in the analysis.

Assessing Probability

Risk assessments, by definition, evaluate probability (likelihood), as it is part of the overall formula (Risk = probability X impact). However, it is also common for probability to be included in the other IVA approaches (e.g., Almodovar-Rosario and Dorney 2014; City of Carlsbad 2017; NJTPA 2011; San Francisco BCDC and MTC 2011). Many exposure assessments, scenario planning projects, and indicator-based VAs qualitatively address the likelihood of an event, hazard, or stressor (at least implicitly, choosing to model a 100-year flood event, for example). Understanding the likelihood of an event can play a significant role when evaluating potential adaptation options.

Determining the probability of climate or hazard impacts can be problematic due to lack of data, disagreement between models, and uncertainty regarding the magnitude of change. However, some hazards/stressors have an abundance of data, which makes it easier to quantify probability. In its VA, the City of Everett, Washington discussed the probability of occurrence for several hazards. Earthquake probability was quantified in a detailed manner using probabilistic U.S. Geological Survey models, while probability of flooding was assessed more qualitatively, projecting a general increase of intense storms with future climate change (City of Everett 2018). Similarly, the Territory of American Samoa developed a multi-hazard mitigation plan that evaluated the annual probability of each hazard, using historical data. The historic occurrence of cyclones was well documented, and therefore, the probability was more readily quantified. However, landslide events (which are known to be common) are underreported, resulting in a less robust calculation of probability (Jamie Caplan Consulting 2015).

Choosing a specific climate change or hazard scenario, and a timeframe to evaluate inherently incorporates probability. Many studies include exposure scenarios derived from storm surge models (e.g., Murdukhayeva et al. 2013; Peek et al. 2015b; c; d; e; 2017a; b; c; d; e; f; g; h; i; j; k; l; 2018; RK&K 2016; Tormey et al. 2018a; b); by selecting a particular storm surge category and timeframe of analysis (e.g., a category 2 storm and the year 2050), an assumption is made that the probability of the event is high (over the specified time period).

Probability is also inherently addressed when choosing which climate change factors or hazards to include within an IVA. An inland national park would not assess SLR vulnerability, because the probability of that stressor occurring is very low, just as a low relief barrier island park would not evaluate landslides. Therefore, while probability is not specifically calculated, initial assumptions are made regarding likelihood. This accounts for the wide range of hazards addressed within IVA approaches, as hazards directly relate to geography.

Evaluating Adaptation Options

Generally, adaptation means anticipating the effects of climate change (or natural hazards) and taking steps to avoid or minimize damage. Adaptation strategies can be proactive or reactive and can be implemented at a wide variety of scales. A building may be elevated to avoid future SLR (proactive), or in response to previous flooding from storm surge (reactive). Many strategies focus on a specific asset (e.g., elevating a road above flood levels; Roalkvam 2015) and others are on a system of assets (e.g., reducing future development in hazardous areas; Andrew et al. 2015; Jamie Caplan Consulting 2015). The level of detail in an evaluation may range from a general discussion of adaptation strategies (e.g., RK&K 2016,) to an asset-specific cost-benefit analysis or model-based engineering assessment (e.g., Beavers et al. 2016; Parsons Brinckerhoff and ICF International 2014).

Evaluating potential adaptation strategies based on an IVA is common (e.g., Bonham-Carter et al. 2014; Choate et al. 2017; GHD 2014; HES 2017; Jamie Caplan Consulting 2015; ODOT 2014; Roalkvam 2015; RK&K 2016; SGS Economics and Planning 2010), and most studies suggest that adaptation is the desired outcome of an any assessment of vulnerability (not just infrastructure). Queen Anne's County, Maryland used results from a SLR and storm surge exposure assessment to analyze potential adaptation strategies for different resources, including infrastructure (RK&K 2016). This study grouped strategies into six primary categories: 1) avoid, 2) accommodate, 3) protect, 4) retreat, 5) build adaptive capacity, and 6) no action. Short-, medium-, and long-term adaptation strategies were assessed for each of the six categories. Finally, the study recommended several opportunities to incorporate results of the IVA and adaptation strategies analysis into the county planning processes.

Adding an economic component can be a valuable part of an assessment of adaptation strategies (e.g., Almodovar-Rosario and Dorney 2014; Armstrong et al. 2016; Choate et al. 2017; FHWA 2016; Nelson et al. 2015; ODOT 2014; Parsons Brinckerhoff and ICF International 2014). This is often in the form of a cost-benefit analysis, which can prioritize adaptation by determining which strategies will likely have the highest net benefit (often under a range of possible scenarios). Results of this type of analysis can provide a comparison of the adaptation options and highlight the value of avoiding potential climate and hazard impacts. However, a thorough cost-benefit analysis requires substantial additional information (and time), including data related to the social, economic, and environmental benefits of potential adaptation strategies.

Completing an in-depth analysis of adaptation strategies and an economic analysis can be time-consuming, and therefore, studies often focus on a few critical assets or areas of interest. The Gulf Coast Study (Parsons Brinckerhoff and ICF International 2014) focused on several adaptation case studies based on the VA results. One of these case studies was on culverts and the response to flooding on one creek within the study area. Hydraulic analyses conducted on three different adaptation options (increasing the number of culverts, increasing the size of culverts, and implementing new drainage patterns) helped to evaluate the potential impacts of a 100-year flood on the surrounding area. Finally, an economic analysis suggested which of the adaptation options would likely have the highest overall benefit.

Considerations and Challenges

Scale, Resolution, and Vulnerability Assessment Targets

Scale plays a major role in determining the IVA approach and methodologies. Within this section, the term “scale” refers strictly to the resolution (granularity) of the analysis (not the geographic extent or scope of the study). The scale of an IVA can be categorized in two ways: spatial scale and infrastructure scale (Figure 2-2). Spatial scale (e.g., site-specific, community, regional, park, or state level) is related to hazard-specific metrics, including exposure and probability. Infrastructure scale (e.g., component, asset, or system level) is related to asset-specific metrics, including sensitivity, adaptive capacity, and impact.

There can be a wide variety of spatial scales (resolutions) used for IVAs. Several assessments evaluate the vulnerability of infrastructure at the asset-site level. These fine-grained studies focus on the hazard exposure (or probability) of the asset location and immediately adjacent grounds, which can provide a high degree of detail (Figure 2-2). Most of the indicator-based VAs evaluated use an asset-site level spatial scale (e.g., DeFlorio et al. 2014; HES 2017; ICF International 2012a; b; 2013a; b; 2014a; b; Murdukhayeva et al. 2013; Peek et al. 2015b; 2017a, 2018; Ricci et al. 2019a; b; RK&K 2016; Tormey et al. 2018a; b; VDOT 2011). As the spatial scale increases (coarsens) from the asset-site level to community (e.g., AECOM 2010; 2012; Brooks and Clark 2015), regional (e.g., Genivar Consultants 2010; GHD 2014; Rasmussen et al. 2012; Simmons et al. 2015), or park (e.g., Monahan and Fisichelli 2014) levels, the results for exposure (or probability) become more generalized.

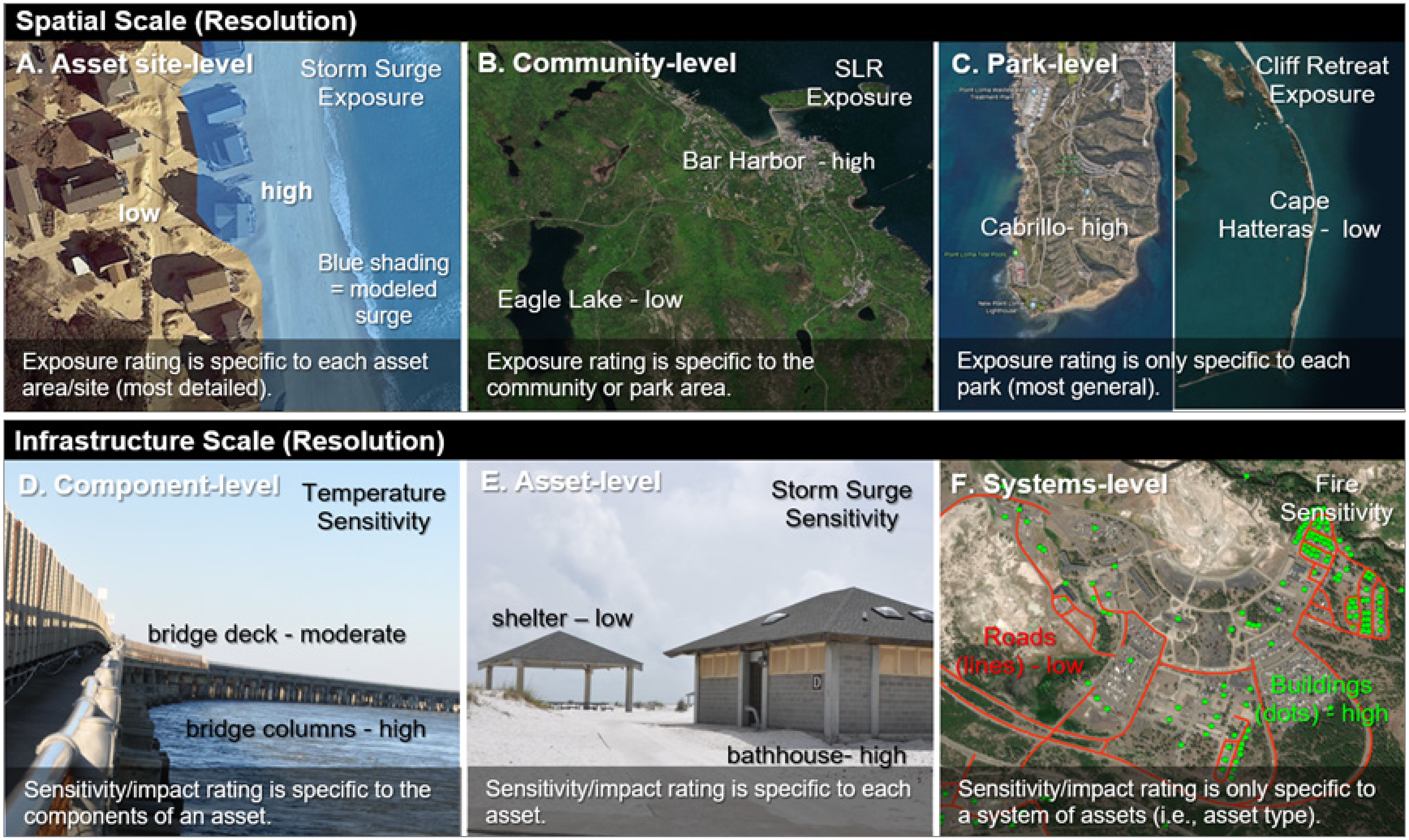

Figure 2-2. Example of common spatial (A-C) and infrastructure scales (D-F) within the studies evaluated. A) Asset site-level studies evaluate and score the exposure/probability of each asset site area (most detailed, highest resolution). B) Community-level studies evaluate and score the exposure/probability of each community. C) Park-level studies evaluate and score the exposure/probability of each park (most general, lowest resolution). D) Component-level studies evaluate the sensitivity of each part/component of an asset. E) Asset-level studies evaluate and score the sensitivity/impact of each individual asset. F) Systems-level studies evaluate and score the sensitivity/impact of entire systems.

There are three primary infrastructure scales (resolutions) used in the evaluated IVAs: component, asset, and systems (Figure 2-2). Component (high resolution) studies evaluate the individual elements of an asset, such as the deck, columns, and footings of a bridge. These studies are less common, as they require detailed engineering data and a high level of expertise (e.g., Genivar Consultants 2010). Asset-level IVAs examine infrastructure at the scale of individual buildings, roads, trails, bridges, etc. (e.g., City of Boston 2016; ICF International 2012a; b; 2014a; b; Murkukhayeva et al. 2013; Peek et al. 2015c; 2017d; 2018; Tormey et al. 2018a; b; WCU and NPS 2016). These IVAs can also be time-intensive, as agencies often manage hundreds to thousands of assets. To address this issue, studies may use criticality as a filter (e.g., Abkowitz et al. 2015; Cambridge Systematics 2015; Hogan et al. 2014; ICF International 2011; ICF International and PB Americas 2011; Merrill and Gates 2014) or conduct a less in-depth assessment such as evaluating exposure only (e.g., Peek et al. 2015a; in press; RK&K 2016). Indicator-based VAs are commonly conducted at the asset-level scale because it is less challenging to determine indicators for sensitivity and adaptive capacity than at the systems scale. Systems-level (low resolution) IVAs typically involve the evaluation of a group of assets that share a particular purpose or function (e.g., road, trail, and utility systems). Utilizing a systems-level scale approach assumes each asset type will have similar sensitivity, adaptive capacity, or impact in response to a hazard or stressor (e.g., AECOM 2010; Brooks and Clark 2015; City of Carlsbad 2017; GHD 2014; MassDOT 2016). Results for systems-level scale IVAs are more generalized; however, this may be unavoidable due to data and time constraints.

Many IVAs (e.g., WCU and NPS 2016) typically target assets such as buildings, structures, roads, and bridges. A key observation from this review of IVAs is that most do not include a detailed assessment of utilities and systems (e.g., energy, water, waste, and communications). This observation is critical to consider when developing a future IVA protocol.

Data Issues

Data availability and access can create challenges during an IVA and can influence both the type of assessment that is appropriate, and how in-depth the project will be. Common data issues for IVAs include poor quality, low resolution, and lack of coverage (e.g., no data that is park or statewide). In addition, databases can often be incomplete, poorly maintained, or obsolete. Finally, when assessing risk, the likelihood or probability of an event in a specific area is often difficult to quantify (e.g., probability of an earthquake within a park).

Within an IVA, there can be several issues related to natural hazards and climate change data. One of the major issues is a lack of mapped or recorded hazard data (e.g., Armstrong et al. 2016; ICF International 2016). For example, detailed FEMA flood maps have not been developed for many national parks, like YELL, where the entire park has been mapped as a D zone (i.e., possible but undetermined flood hazards, no analysis conducted). Similarly, mapped data may be available, but not appropriately scaled to the study area (e.g., AECOM 2010; 2012; HES 2017; MDOT et al. 2014; Winguth et al. 2015). Researchers in Australia noted one major limitation in conducting a VA in the Australian Capital Territory was that the resolution of the temperature climate models could not capture the urban heat island effect (AECOM 2010).

There are also issues related to infrastructure attribute databases. In some cases, an appropriate infrastructure database may not exist. In other cases, the database may be incomplete, or the attribute data may not be a good indicator for measuring sensitivity, adaptive capacity, or potential impact (within risk). ICF International completed several pilot IVAs for the NPS (ICF International 2012a; b) and the FWS (ICF International 2017). At this time, sensitivity and adaptive capacity indicators were taken directly from asset management databases. At ASIS, the facility condition index from the NPS's facilities management database was the basis for sensitivity, and current replacement value was the basis for adaptive capacity. Using attributes from this database as indicators for vulnerability did not fully capture how the asset would fare when exposed to a hazard or stressor. The facilities condition index is a factor of the projected cost of repairs (deferred maintenance, recurring maintenance deferred, and component renewal deferred) and the current replacement value of an asset (NPS 2018). However, the ASIS study evaluated hazards including storm surge and SLR but did not include any sensitivity indicators directly related to flooding, such as whether the building is elevated above the ground or built to storm-resistant standards. Other studies have found that using multiple hazard-specific indicators can be a more effective way to measure sensitivity, adaptive capacity, and potential impacts (e.g., Cambridge Systematics 2015; Maryland State Highway Administration and Santec Consulting Services 2014; Peek et al. 2015b; c; d; e; 2017j; k; l; 2018; Tormey et al. 2018a; b).

Indicator Types

Some assessments evaluate purely the physical vulnerability of infrastructure, while others address the components of vulnerability (in particular sensitivity and adaptive capacity) from a functional or economic perspective (e.g., ICF International 2014a; San Francisco BCDC and MTC 2011; WSDOT 2011). Physical sensitivity indicators for a road corridor might include attributes such as condition, construction, and materials; a functional indicator might include the length of time the road would be unusable after an event. For adaptive capacity, one physical indicator might be the size/weight of the asset (larger assets would be harder to relocate), whereas an economic indicator might be the expense of adapting (it might be harder to fund if the costs are too high).

Transportation-focused VAs often include functional indicators for sensitivity and adaptive capacity. The FHWA San Francisco Bay case study used level of use as one indicator for sensitivity and the availability of alternate or similar routes for adaptive capacity (San Francisco BCDC and MTC 2011). Also, the WSDOT used functional indicators (travel disruptions, road closure, and reduced commerce) when measuring the potential impact of climate change to transportation assets (WSDOT 2011). Functionality is more frequently incorporated into transportation VAs (compared to other infrastructure), as these assets are designed to be included in networks and systems (e.g., roads, trails, and bridges).

Economic factors are most often included as indicators for adaptive capacity. For example, an asset's replacement value has been used as an adaptive capacity indicator within FHWA (ICF International 2014a), FWS (ICF International 2017), and NPS (ICF International 2012a; b) studies. The rationale for using replacement value is that more funding and resources would be required to maintain, repair, or replace the asset when damaged (ICF International 2017).

Scoring Vulnerability

There are a wide variety of vulnerability scoring methods within the studies evaluated. Many studies are qualitative and do not assign a vulnerability score (to assets or systems), but instead include a general discussion of the hazards and impacts (e.g., Anderson et al. 2015a; Place Matters 2011; Simmons et al. 2015). Other studies score vulnerability semi-quantitatively, ranking assets on a simple low-moderate-high (or similar) scale (e.g., City of Carlsbad 2017; ICF International 2012a; b; 2017; Peek et al. 2015b; c; d; e; 2017a; b; c; d; 2018; Tormey et al. 2018a; b; WCU and NPS 2016). More quantitative studies incorporate additional factors, such as probability, weighting of indicators, computer models, or engineering analyses (e.g., Genivar Consultants 2010; Hogan et al. 2014; Jamie Caplan Consulting 2015).

Using indicators to score adaptive capacity is particularly difficult for infrastructure (and other non-living resources) and incorporating that score into the overall vulnerability can be problematic. Indicators for both asset exposure and sensitivity are most commonly physical in nature. Exposure is related to the physical location of the asset compared to a hazard, and sensitivity is how the asset would fare due to its physical characteristics (e.g., the asset is in good condition, is protected by engineering, and is built of storm-resistant materials). However, the adaptive capacity of infrastructure is complex, as it can be dependent on numerous, often hard to measure or calculate, factors. The adaptive capacity score of infrastructure includes both intrinsic factors (the physical barriers to adaptation due to the properties of the asset) and extrinsic factors (e.g., the social, economic, or organizational barriers to adaptation).

Some organizations attempt to evaluate and score adaptive capacity for infrastructure using a combination of these complex factors. The NPS does not evaluate adaptive capacity for non-living resources (e.g., infrastructure), but instead considers management response to be part of adaptation and evidence of *organizational* capacity to adapt.

2.7 Best Practices and Recommendations

The following sections discuss the ideal approach for evaluating the climate change and natural hazards vulnerability of infrastructure, with best practices and recommendations specific to assets within the NPS. These recommendations focus on the intrinsic (physical) vulnerability of infrastructure to the hazard or climate change stressor at the asset/site level scale or resolution (Figure 2-2).

Clarify Extrinsic Versus Intrinsic

Vulnerability assessments commonly include both intrinsic (physical) and extrinsic (e.g., functional and economic) factors as part of the overall vulnerability score. While evaluating both the intrinsic and extrinsic aspects of vulnerability is a beneficial practice, combining these factors when scoring each asset can confuse or complicate the final vulnerability results. For instance, it is possible to have an asset that has high intrinsic (physical) vulnerability to a hazard (e.g., a small, dilapidated shed that is being inundated by SLR), that also has a low extrinsic vulnerability (e.g., has low priority, value, and utility). Combining these factors into one vulnerability score can dilute (or conversely, exaggerate) the physical threat of the hazard, which could negatively impact future decision making and planning for assets. Evaluating and reporting intrinsic and extrinsic vulnerability separately provides greater clarity and accuracy for decision-makers and managers.

Address Criticality

Criticality is commonly addressed as part of an IVA process. Ideally, criticality is scored separately from the physical vulnerability of assets, either before the IVA to narrow down the quantity of assets to be evaluated, or after to help prioritize adaptation strategies. One recommended approach for assessing criticality of assets is a hybrid approach, which uses a combination of a quantitative analysis and qualitative stakeholder/expert opinion (ICF International 2011). The NPS commonly utilizes the asset priority index within FMSS to help determine the criticality of assets. While this is a quantitative way to evaluate criticality, the asset priority index is typically used for funding decisions and does not represent the absolute criticality of the asset. The FHWA typically incorporates operational/functional and economic data sources when assessing criticality (e.g., traffic volume, evacuation routes, detour length, cost of replacement), which could be a useful approach for evaluating the criticality of NPS transportation infrastructure. It is also important to consider the integrated nature of assets within a system (e.g., energy and water delivery systems are critical to nearly all park buildings). Qualitative methods for evaluating criticality can vary, but when possible, it is advisable to include a range of park personnel, partners, and experts, particularly those who have institutional knowledge of the assets.

Complete a Detailed Exposure Assessment

Exposure is the foundation of any IVA. If an asset is not exposed to a particular natural hazard or climate stressor, it is not meaningful to evaluate its sensitivity (or impact). Robust exposure assessments utilize scientific data and models related to the extent of the stressor/hazard. Completing a detailed asset-specific exposure assessment requires good data, which should be scientifically reviewed, spatially appropriate, well maintained, and up to date. Ideally, data should be of a high enough resolution to show variability between assets and mapped continuously over the entire region of interest.

While an exposure assessment could be a simple geospatial desktop exercise, a best practice is for the analysis to be conducted (or at least reviewed) by a subject matter expert. Even the most robust spatial data can have errors and model inaccuracies that are more likely to be recognized by someone with proper training. In addition, ground-truthing the data can increase the likelihood of recognizing data issues and can improve the accuracy of the final exposure results. As a final quality check, it is recommended that the resulting exposure scores be reviewed by personnel with institutional knowledge of the infrastructure and/or hazards.

Evaluate Sensitivity

In addition to exposure, a sensitivity analysis is vital for a complete IVA. Robust analyses rely on indicators (i.e., factors that represent or characterize how the asset will fare when exposed) to evaluate an asset’s sensitivity. For infrastructure, indicators related to the physical attributes of the asset, such as condition, construction/materials, resistance/resilience, and engineering, are most useful. Federal asset databases are often mined for information relevant to infrastructure sensitivity indicators. One example of a good data source for sensitivity is the FHWA National Bridge

Inventory, which has over 100 categories that describe the physical attributes of each bridge and is updated annually. In addition, the NPS Wildland Fire Risk Assessment database contains detailed information related to the construction and materials of structures within national parks. These databases can contain a large quantity of information regarding each asset; however, these attributes do not always well represent the sensitivity of an asset to a particular hazard. For example, some studies have used the facilities condition index within FMSS as a proxy for physical condition (degree of deterioration), however, this attribute is in fact calculated using the asset's deferred maintenance and current replacement value.

Sensitivity indicators can be difficult to assign for infrastructure, and often science-based data does not exist for these indicators. When sensitivity data is lacking, it is recommended that indicators still be used for the hazard or stressor. In these cases, subject matter experts can be used to evaluate and score each sensitivity indicator. Some studies utilize surveys or workshops to collect sensitivity indicator data for infrastructure (e.g., NPS 2017a; WCU and NPS 2016). Using experts to score specific indicators, as opposed to a generalized ranking of sensitivity, can provide greater detail and improve the accuracy of the assessment results.

Evaluate Probability and Potential Scenarios
Including probability in an IVA can be useful, as it can provide managers with the likelihood of an event, hazard, or stressor. Probability data is not always easy to quantify, and therefore, may be qualitative in nature. In these cases, it may be useful to assess probability using expert opinion, workshops, or surveys. Finally, analyzing multiple future scenarios (e.g., SLR rates, multiple time frames, storm surge scenarios) in combination with probability, can lead to more informed future planning and adaptation strategies.

Evaluate and Prioritize Adaptation Strategies
Adaptation to natural hazards and climate change is the ultimate goal of most IVAs, and therefore, evaluating potential adaptation strategies is the next logical step following the vulnerability process. Making adaptation decisions for infrastructure can be extremely complex, and multiple factors should be considered, including physical, economic, social, and political. A thorough examination of these factors can help inform the selection of appropriate adaptation strategies.

It is recommended that the evaluation of adaptation strategies is performed in a team or workshop format, where multiple internal and external parties are involved (e.g., park staff, partners, and subject matter experts). In addition, incorporating the IVA results and subsequent adaptation strategies into relevant park planning documents and processes can increase the overall impact and utility of the VA. Implementing effective adaptation strategies will reduce an asset's exposure or sensitivity to a natural hazard or climate change stressor, which lowers overall vulnerability.

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Chapter 3: A Review of Vulnerability Assessments for Natural Resources of the National Park Service

Julia L. Michalak, Joshua J. Lawler, Michelle Agne, Robert Emmet, Hsin-Wu Hsu, Vivian Griffey

School of Environmental and Forest Sciences
University of Washington

Cumberland Island National Seashore. (©PROGRAM FOR THE STUDY OF DEVELOPED SHORELINES, WESTERN CAROLINA UNIVERSITY)

Please cite this chapter as:

Michalak, J.L., J.J. Lawler, M. Agne, R. Emmet, H. Hsu, and V. Griffey. 2022. Chapter 3: A review of vulnerability assessments for natural resources of the NPS. Pages 63-93 *in* Peek, K.M., B. R. Tormey, H.L. Thompson, A. C. Ellsworth, and C.H. Hoffman (editors). 2022. Climate change vulnerability assessments in the National Park Service: An integrated review for infrastructure, natural resources, and cultural resources. Natural Resource Report NPS/NRSS/CCRP/NRR—2022/2404. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/nrr- 2293650.

3.0 Executive Summary

Climate change poses a significant threat to the natural resources currently conserved in parks, preserves, and other protected areas. An initial step in addressing potential climate impacts is to assess the vulnerability of those resources to projected changes in climate. Numerous frameworks, approaches, and tools are available for assessing vulnerability. This study systematically searched the literature to identify climate change vulnerability assessments of natural resources within national parks that are included in the National Park Service Inventory and Monitoring Program. The review ultimately identified 71 assessments with either an explicit or implicit goal of evaluating natural resources climate change vulnerability in a way that could inform park management (Appendix E). These 71 natural resources vulnerability assessments were examined to identify 1) common approaches to conducting natural resources vulnerability assessments, 2) which parks have been evaluated and to what extent, and 3) recommendations for conducting future natural resources vulnerability assessments.

Based on this review, four natural resources vulnerability assessment types were identified: 1) general, 2) broad-scale screens, 3) systematic multi-target evaluation, and 4) single resource or process assessments. General natural resources vulnerability assessments synthesize existing vulnerability research and data to provide a broad overview of climate impacts, and relate those to potential vulnerabilities for a range of priority resources. Broad-scale screens use widely available datasets, such as climate or landscape variables, to systematically quantify selected aspects of climate change vulnerability across a large subset of park units. Systematic multi-target natural resources vulnerability assessments use a consistent methodology, such as range-shift modeling, to evaluate and compare vulnerability for multiple resource targets within a single group (e.g., multiple bird species or desert plant habitats). Single resource or process assessments provide an in-depth assessment of a single species (e.g., whitebark pine), habitat (e.g., mangroves), or process (e.g., sea-level rise, storms, or fire). Although general and single resource assessments were the most common, broad-scale screens and systematic multi-target natural resources vulnerability assessments covered a larger number of parks.

Nearly all the Inventory and Monitoring parks have been included in at least one natural resources vulnerability assessment to date, but 41% of these have only been evaluated by broad-scale screen assessments that evaluate a small number of vulnerability metrics and do not account for individual park characteristics. An additional 36% of Inventory and Monitoring parks have also been evaluated by a systematic multi-target evaluation, but not a general or single resource/process natural resources vulnerability assessment. About 14% of Inventory and Monitoring parks have been the subject of a general natural resources vulnerability assessment and 12% have been included in a single resource/process assessment. Although nearly all parks were included in at least one natural resources vulnerability assessment, most parks were included in natural resources vulnerability assessments that focused on a small subset of resources or potential climate impacts. Only 23 parks had a comprehensive assessment that synthesized existing climate change vulnerability data to identify key climate impacts and vulnerabilities to priority resources.

The frequency and type of natural resources vulnerability assessments differed by geographic region. Systematic, multi-target assessments were common for parks in the eastern U.S. (i.e., the Northeast, Southeast, Midwest, and National Capital regions) while general assessments were rare in these regions. Parks in the western U.S. (i.e., Pacific West and Intermountain regions) were less likely to be included in any natural resources vulnerability assessment (broad-scale screens excluded), but in-depth, general natural resources vulnerability assessments were more common for western parks that were evaluated. Natural resources vulnerability assessments for parks in Alaska, Hawaii, and other offshore islands usually evaluated a single resource target or process.

This study recommends a set of best practices for conducting natural resources vulnerability assessments for national parks and for protected areas in general. Basic recommendations include addressing multiple aspects of vulnerability including sensitivity, exposure, and adaptive capacity, using multiple approaches to evaluate vulnerability, addressing uncertainty, and using existing vulnerability data when possible. Nearly all the studies addressed uncertainty in some way, most commonly by using multiple alterative climate scenarios to evaluate a range of potential future impacts. General natural resources vulnerability assessments were more likely to synthesize existing vulnerability information; the most comprehensive of these integrate information from a range of different approaches (i.e., model projections, historical trends, and trait-based assessments). Of the 40 natural resources vulnerability assessments that explicitly claimed to evaluate vulnerability, only about half directly addressed at least one of these three aspects of vulnerability and only 11 addressed all three. However, the remaining studies all evaluated aspects of sensitivity and exposure, although they did not explicitly use those terms.

Beyond specific content recommendations, we conclude that each natural resources vulnerability assessment type has different strengths and weaknesses to consider when selecting an assessment approach. Each approach is useful under certain circumstances, and ultimately, implementing multiple assessment types will likely be most effective to fully understand vulnerability. For example, a general natural resources vulnerability assessment can synthesize existing information, weigh information from multiple vulnerability assessment approaches, and identify key vulnerabilities. However, general natural resources vulnerability assessments are unlikely to include enough detailed, quantitative information to support management plans for individual species or resources. By contrast, single-resource assessments have a very narrow scope, but can develop detailed models or analyses that can be more informative for setting management targets. A second recommendation is for parks with similar geographic, climatic, and ecological conditions to partner in conducting vulnerability assessments whenever possible. Many climate impacts and natural resources are regional, so a single natural resources vulnerability assessment can effectively and efficiently evaluate vulnerabilities for multiple parks simultaneously. Finally, a few natural resources vulnerability assessments that we reviewed moved beyond evaluating vulnerability to also identifying potential adaptation strategies. Integrating adaptation planning into the vulnerability assessment process will produce more actionable assessments and advance the critical need for climate change adaptation strategies to reduce negative climate impacts on natural resources.

3.1 Acknowledgments

We are particularly grateful to Cori Currier, Alex Gustafson, Sarah Harrison, and Olivia Hill for help developing the methods and analyzing the studies. We are also indebted to John Gross, Cat Hawkins-Hoffman, and Rebecca Beavers for input and guidance. This work was funded by a grant from the U.S. National Park Service.

3.2 Acronyms

CCVI: Climate Change Vulnerability Index

CVI: Coastal Vulnerability Index

GCM: General Circulation Model

HCCVI: Habitat Climate Change Vulnerability Index

I&M: Inventory and Monitoring (NPS)

NPS: National Park Service

NRVA: Natural Resources Vulnerability Assessment

SLAMM: Sea Level Affecting Marshes Model

SLOSH: Sea, Lakes, and Overland Surges from Hurricanes Model

SLR: Sea-Level Rise

VA: Vulnerability Assessment

VIC: Variable Infiltration Capacity Model

3.3 NPS Unit Codes

ACAD: Acadia National Park

CRLA: Crater Lake National Park

EVER: Everglades National Park

GLAC: Glacier National Park

GRSM: Great Smoky Mountains National Park

GRTE: Grand Teton National Park

MORA: Mount Rainier National Park

NOCA: North Cascades National Park

OLYM: Olympic National Park

YELL: Yellowstone National Park

3.4 Introduction

Climate change already affects ecosystems around the world. Warming temperatures and changing precipitation patterns have caused shifts in species distributions, changes in phenology, altered behavior, and altered interspecific interactions (IPCC 2014). Extinction risks for global taxa are projected under climate change ranging from 2.5% under present warming, to 16% if average global temperatures reach the 4.3°C rise projected under our business-as-usual greenhouse gas emissions [Representative Concentration Pathway 8.5] (Urban 2015). Despite their status, protected areas are not immune to the impacts of climate (e.g., Scriven et al. 2015; Zomer et al. 2015). National parks are warmer than they have been for much of the 20th century (Gonzalez et al. 2018; Monahan and Fisichelli 2014) and many are projected to experience significant changes in their climates, biota, and coastlines (e.g., Gonzalez 2017; Hameed et al. 2013; Pendleton et al. 2004; Wu et al. 2018).

Assessing vulnerability is an important step in understanding and planning for potential climate impacts (Glick et al. 2011). Climate change vulnerability can be defined as the degree to which a system or a component of that system is likely to be harmed by climate change and is often described as being a function of three distinct elements—exposure, sensitivity, and adaptive capacity (Turner et al. 2003). Exposure is the extent to which a species or system experiences climate change or a climate-driven change in environment (Dawson et al. 2011). Sensitivity to climate change can be defined as the degree to which climate changes impact the species or system's survival, functioning, or performance (Dawson et al. 2011). Adaptive capacity is the ability of a species or system to adjust to, moderate, or cope with climate change (Dawson et al. 2011).

Guidance for assessing climate change vulnerability of species and ecological systems is readily available (Dawson et al. 2011; Glick et al. 2011; Pacifici et al. 2015). Such guidance includes recommendations for designing assessments, selecting targets, choosing data sources, and approaches for evaluating each of the three components of vulnerability. For example, assessments that incorporate uncertainty about future climate conditions into vulnerability estimates are more useful than those based on a single projected future (Glick et al. 2011). Additionally, assessments that integrate multiple lines of evidence to evaluate vulnerability are likely to be more useful than those that rely on a single assessment approach (Michalak et al. 2017).

Numerous climate change vulnerability assessment (VA) tools exist, including trait-based indices, databases, and worksheets (Bagne et al. 2011; Case et al. 2015; Young et al. 2010). In addition, assessments have drawn on historical and projected climatic changes, bioclimatic model projections, and species traits (Foden et al. 2013; Pacifici et al. 2015). Here we review climate change natural resources vulnerability assessments (NRVAs) conducted within U.S. national parks. We explore which parks have been included in a NRVA and characterize the NRVAs in terms of which resources have been assessed, what assessment approaches and data types are used, and which aspects of climate change vulnerability are commonly evaluated. We use the results of the review, in conjunction with previously published guidance on conducting VAs, to identify a framework for conducting VAs at a variety of scales, and to provide a set of best practices for conducting further VAs in national parks and in protected areas in general.

3.5 Methods

In January and February 2018, we searched for VAs of national parks using Web of Science, Google Scholar, and National Park Service (NPS) document databases based on NPS park units on the Inventory and Monitoring (I&M) list (n = 289 park units, hereafter referred to as "parks" or "park units"), and including every type of park unit (e.g., National Park, National Historic Site) in our search. In searching for VAs of each park, we included the name of the park, "climate," and "change" in our search terms. We also searched more generally on the terms "national park," "climate," and "change." Finally, we included any additional VAs cited in Gonzalez (2017).

After searching for VAs, we used the following criteria to narrow the scope of our study to climate change NRVAs of national parks. We only included papers that were specific to national parks—i.e., we excluded papers that simply assessed resources that happened to fall within parks without focusing on the park itself as the primary study area. We did, however, include papers assessing the region surrounding a park if the primary focus of the paper was park management. We also only included papers that could inform park management, either explicitly or implicitly. We only included papers whose purpose was to assess climate change impacts on national parks, rather than quantify climatic variability in general or identify threats not directly related to climate change.

We evaluated all papers that met these criteria regardless of whether they explicitly claimed to evaluate climate change vulnerability. We developed a scheme to categorize NRVAs into common types and classified each NRVA by type. In addition, we identified the parks included in each NRVA, determined the target(s) of each assessment (e.g., species, ecosystems), which of the three elements of vulnerability were assessed, what kinds of data or evaluation approaches were used, and whether NPS staff were included as authors of the assessment. Each study was reviewed by one of eight evaluators. We assessed inter-reviewer reliability by having all reviewers assess the same set of five papers. A final review of all NRVAs was conducted by a single reviewer to ensure consistency.

3.6 Results

Our initial search returned 282 documents. From these, we identified 119 that described climate change impacts on natural resources within parks as opposed to more general studies investigating aspects of climate associated with natural resources. Within these 119 documents, we identified 40 that explicitly claimed to evaluate climate change vulnerability and 31 that implicitly evaluated climate change vulnerability (see Box 3-1). The remaining 48 studies described research on climate change impacts or discussed climate change vulnerability but did not meet the criteria for being an assessment. The following results are based on explicit and implicit NRVAs combined (n = 71) unless otherwise noted.

Although we attempted to be as comprehensive as possible in our search, there are likely additional studies that fit the criteria for explicit or implicit NRVAs (Box 3-1) but were not identified in our searches. We would like to note that the Adaptation Partners program led by the U.S. Forest Service is conducting NRVAs that include national parks in the western U.S. (http://adaptationpartners.org/). We included 3 NRVAs from this effort, including one that was in final draft form at the time of our review. The Forest Service is leading other NRVA efforts that will include national parks, particularly in the northern Rockies and Sierra Nevada Mountains, but reports for those regions are not yet available. In addition, we missed some studies because we did not search for "protected areas" or "preserves." Although we are aware of studies that explored aspects of climate change vulnerability for protected areas across North America, which would include national parks, these papers did not specifically focus on the parks themselves and did not fit cleanly into this review.

Box 3-1: Definitions of explicit and implicit climate change NRVAs

Explicit NRVA: These studies specifically claimed to evaluate "climate vulnerability,", "climate exposure," or "climate sensitivity" and used at least one of those terms.

Implicit NRVA: These studies never used the term "vulnerability" in a climate change context, but their purpose was to evaluate potential future changes in one or more park natural resources due to climate change. These may have used the terms climate disruption, climate impacts, or climate assessment to describe their efforts. Implicit NRVAs did not frame climate impacts in terms of exposure, sensitivity, or adaptive capacity, though they implicitly addressed one or more of these.

Excluded from NRVA designation: We excluded studies that did not identify potential future changes in park natural resources. These included studies that examined the relationship between the resource and climate variability, developed a model or methodology that could evaluate future changes, developed scenarios that could be used in a vulnerability analysis, or evaluated historical trends in climate and resource levels without explicitly extrapolating to future changes.

Natural Resources Vulnerability Assessment Types

The NRVAs we reviewed spanned a wide range of spatial scales and conceptual scopes. We identified four main types: 1) general, 2) broad-scale screens, 3) systematic multi-target evaluations, and 4) single resource or process assessments. General NRVAs synthesize existing research and data to provide a broad overview of potential or modeled climate impacts, and link those impacts to plausible or expected changes in a range of priority resources. Broad-scale screens systematically quantify selected aspects of climate change vulnerability across a large subset of park units (e.g., Hansen et al. 2014). Systematic multi-target NRVAs use a consistent methodology to evaluate and compare vulnerability for a range of resources within a single group (i.e., multiple bird species or desert plant habitats). Single resource or process assessments provide an in-depth assessment of a single species, habitat, or process (i.e., sea-level rise [SLR], storms, or fire).

General Natural Resources Vulnerability Assessments

General NRVAs aim to provide holistic assessments of climate change vulnerability as opposed to focusing on any single resource. These assessments can focus on one or more parks and can range from simple conceptual analyses based on a few hours of expert deliberation to in-depth, multi-year assessments. They generally include some description of expected climate changes, an assessment of key vulnerabilities, and a qualitative narrative (more common) or quantitative (less common) assessment of how climate changes could impact priority resources.

Data Inputs and Methods

General NRVAs rely primarily on existing literature, data, and expert knowledge, although new data or models can be developed as part of the NRVA process. A few general NRVAs in our review incorporated a systematic approach such as the NatureServe Climate Change Vulnerability Index

(CCVI) (Young et al. 2010) or similar (e.g., Amberg et al. 2012), or else incorporated results from vegetation models (e.g., Panek et al. 2009) or climatic niche models (e.g., Gonzalez 2014). However, the majority relied on qualitative explorations of plausible vulnerabilities.

Benefits and Best Applications

General assessments provide an overview of climate changes and big-picture impacts that are likely relevant to many sectors in a park. Because they evaluate a wide range of impacts and resources, they can help identify key climate-related stressors and set priorities for more detailed, future assessments of highly vulnerable resources. Another advantage of a general assessment is that park managers are more likely to be directly involved in the development of the NRVA, and hence in helping to facilitate adoption and integration of the results with park management (Table 3-1). Finally, because general NRVAs draw from existing literature and data, they can synthesize information from a range of different assessment approaches and sources rather than relying on a single assessment method.

Table 3-1. Number of assessments in each climate change NRVA type and within each type, for single or multiple (regional, coastal, or national) parks. The number of assessments with at least one NPS author is listed in parentheses.

NRVA Type	Spatial Extent	#	%
General	Regional	11	–
	Single park	15	–
	Category total	26 (20)	37%
Broad-scale screen	National	5	–
	Regional	1	–
	Category total	6 (5)	8%
Single resource/process	Coastal NPS units	1	–
	Regional	3	–
	Single park	21	–
	Category total	25 (8)	35%
Systematic multi-targets	Regional	7	–
	Single park	7	–
	Category total	14 (8)	20%
Totals	–	71	100%

Limitations

The broad scope of comprehensive assessments limits the amount of detail that can be included for any single resource, although this can be offset by greater investments of time and funding and some assessments are very detailed. In addition, general assessments rely heavily on existing knowledge and data and so are limited by the availability of existing research.

Broad-Scale Screens

Broad-scale screens systematically quantify selected aspects of climate change vulnerability across a large subset of park units and are subsequently used to either classify or rank parks in terms of their vulnerability. Broad-scale screens can aim to evaluate overall climate change vulnerability (Hansen et al. 2014) or target specific vulnerabilities such as changes in phenology (Monahan et al. 2016), air quality (Val Martin et al. 2015), or species turnover (Wu et al. 2018).

Data Inputs and Methods

Broad-scale screens require consistent data sets that cover all or a large subset of park units, generally extending nationwide or larger. National gridded spatial data such as downscaled climate projections or land cover are commonly used. These studies also often incorporate data collected at the service-wide scale, such as data on rare or invasive species (Hansen et al. 2014; Stroh et al. 2016).

Benefits and Best Applications

Broad-scale screens provide a rapid evaluation of many parks simultaneously, as well as consistent metrics to compare or rank vulnerability across numerous parks. They are useful for national and regional planning as well as for resource allocation and provide guidance for more fine-grained assessments.

Limitations

Broad-scale screens draw on a small set of indicators to evaluate vulnerability and so inevitably miss important regional and local characteristics that are often critical to true vulnerability. Given the scope of these assessments, the types of indicators that can be used are generally limited by data availability and often focus on climate exposure or general landscape characteristics. Finally, park managers are less likely to be involved directly in these broad-scale assessments and hence adoption and integration of these assessments into park planning may be limited.

Systematic Multi-Target Evaluations

Systematic multi-target NRVAs use a consistent methodology to evaluate vulnerability across multiple species or habitats. The use of a consistent approach allows for direct comparison and ranking of vulnerability across species or habitats, although authors may or may not choose to do so.

Data Inputs and Methods

The systematic NRVAs we reviewed used a range of methods. The most common approaches were trait-based indices such as the NatureServe CCVI (e.g., Barrows et al. 2014; Comer et al. 2012) and climatic niche models (also referred to as range shift or climate envelope models; Fisichelli et al. 2014). The CCVI uses a combination of literature review, expert knowledge, and climate exposure measures to generate a vulnerability index or score for each species or habitat. Climatic niche models use climate data and statistical modeling to project changes in a species' distribution based solely on climate conditions. Climatic niche models are the most common range-shift model. However, studies have used other approaches such as population-based models (Catano et al. 2015) or habitat-based models (Koch et al. 2015; Shovic and Thoma 2011).

Benefits and Best Applications

These NRVAs provide a systematic and quantitative approach to evaluating vulnerability for species or habitats. When existing tools are used, these assessments can often be relatively quick and require few resources. If desired, they allow for the ranking and identification of the most vulnerable species or habitats which can help identify priority vulnerabilities. Perhaps most usefully, these approaches provide a framework for thinking about what traits contribute to vulnerability, which can be particularly helpful for managers with no previous VA experience. Most importantly, these assessments individually provide important pieces of information that can be combined with other assessments to provide a comprehensive view of vulnerability.

Limitations

Rapid assessments of many species or habitats can be superficial, and reliance on a single method for evaluating vulnerability is not recommended. For example, standardized checklists or tools may miss important aspects of species or habitat vulnerability that are specific to that resource or its location. Similarly, the range-shift models sometimes used in these assessments have significant limitations and fail to account for many important aspects of species vulnerability (Fordham et al. 2012). Integrating results from multiple methods is more likely to produce a robust picture of vulnerability. Finally, these assessments are narrowly focused, limiting the applicability and usefulness of the results outside the species or habitats specifically evaluated.

Single Resource or Process Assessments

As the name implies, single resource or process assessments target one species, habitat, or process (e.g., SLR, storms, or fire). Examples include whitebark pine (Chang et al. 2014; Hansen and Phillips 2015), glaciers (Brown et al. 2010), SLR (Pendleton et al. 2010), and the Kobuk River (Durand et al. 2011).

Data Inputs and Methods

These assessments tend to use resource-specific modeling or experimental studies to develop a detailed and quantitative understanding of the resource's climate change vulnerability. The methods used are tailored to the specific target.

Benefits and Best Applications

These resource-specific assessments provide an in-depth assessment of one resource, often developing a more complete and mechanistic understanding than can be obtained from the more rapid or broader-reaching approaches described above. These assessments are particularly useful to evaluate high-priority resources where management actions will likely be very expensive, contentious, or may have far-reaching consequences, for example keystone whitebark pines in YELL (Iglesias et al. 2015) or resources with high potential vulnerability (e.g., glaciers - Brown et al. 2010, meltwater stonefly - Muhlfeld et al. 2011, coastal everglades ecosystem - Nungesser et al. 2015). These assessments can also be used to fill in data gaps or uncertainties uncovered by previous

NRVAs. In addition, these assessments can serve as components of well-designed and well-funded comprehensive assessments.

Limitations

Resource- or process-specific assessments are both resource and data intensive to develop. They have a narrow scope that limits their applicability and are often done without the collaboration of park staff (Table 3-1), potentially limiting the application of the results to park management.

General and single resource/process assessments were the most common types of assessments, each representing about 35% of the assessments reviewed, followed by systematic multi-target assessments (20%; Table 3-1). This review only identified 6 broad-scale screens (8%). Each of these assessment types could be conducted for one or more parks. Roughly 38% of the studies (n = 27) assessed the vulnerability of multiple parks, and of these, 15 assessments included between 2 and 10 parks. An additional 12 assessments evaluated more than 10 parks. General and systematic assessments were split about evenly between focusing on a single park or a larger group of parks in a region. Single resource or process assessments were more likely to target a single park (Table 3-1).

General NRVAs varied widely in the breadth and depth of information included. After reviewing all the NRVAs, we identified a subset of 10 comprehensive general NRVAs. These were general NRVA reports that completed intensive analyses of potential climate impacts across a wide range of natural resources as part of a formal VA process for specific park units. As a result, these NRVAs are examples of different approaches for developing a detailed, general NRVA for one or more specific parks. The general NRVAs excluded from this designation were either rapid assessments, providing quick data summaries of potential climate changes with minimal context or synthesis (e.g., Gonzalez 2014), or reports summarizing VA processes (e.g., Symstad et al. 2014). One NRVA focused on summarizing historical climatic conditions as a guide for understanding future climate change (Pederson et al. 2010). Another was a general review of vulnerability for western parks without being easily attributable to any individual parks (Saunders et al. 2007). Most of the comprehensive general NRVAs were conducted for a single park (Amberg et al. 2012; Halofsky et al. 2011; Hameed et al. 2013; Loope and Giambelluca 1998; Rodman et al. 2015); however, four were conducted for a regional group of parks (Ashton 2010; Halofsky et al. 2019; Raymond et al. 2014; Saunders et al. 2011).

Spatial Distribution of Natural Resources Vulnerability Assessments

Nearly all (99%, n = 287) of the I&M parks were the subject of at least one NRVA (Table 3-2). However, 41% of I&M parks were only evaluated by a broad-scale screen (n = 118, Table 3-2). Excluding broad-scale screens, nearly 60% of I&M parks have been included in at least one assessment. That number reduces to 25% when focusing solely on explicit NRVAs. About 35% of parks (n = 103) have been included in a systematic NRVA but not general or resource specific assessments. About 14% of I&M units (n = 41) have had a general NRVA, but only 23 of these parks were included in a *comprehensive*, general NRVA. Single resource/process assessments have been conducted in 12% of parks (n = 34) (Figure 3-1, and Table 3-2).

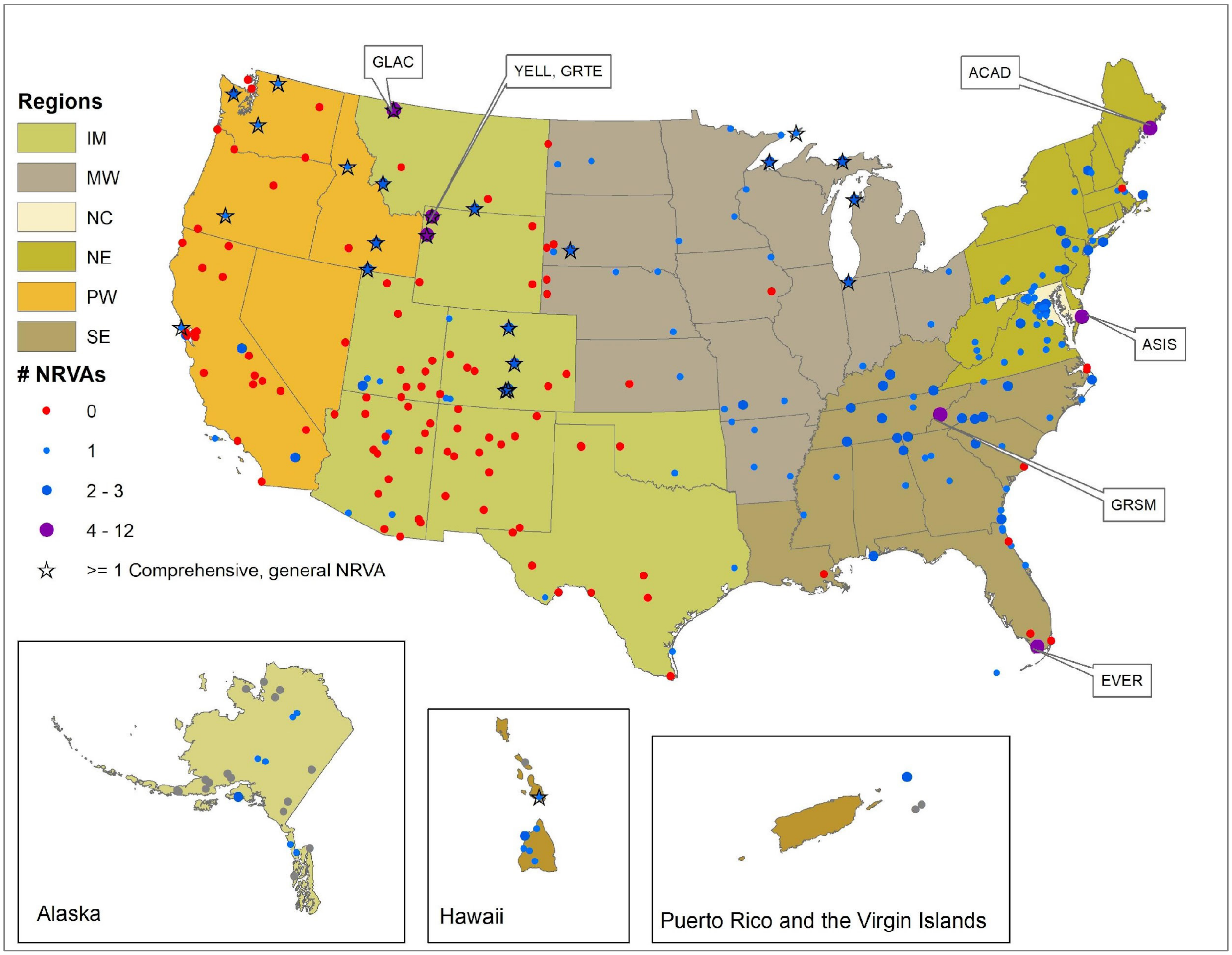

Figure 3-1. Map of the number of explicit or implicit climate change NRVAs (excluding broad-scale assessments) conducted for each I&M national park unit (n = 289 park units). Parks with a star have been included in a comprehensive, general NRVA. Parks with 4 or more NRVAs are labeled. Regions include Alaska, IM (Intermountain), IS (Island parks on HI, PR, or VI), MW (Midwest), NC (National Capitol), NE (Northeast), PW (Pacific West excluding HI), and SE (Southeast).

Table 3-2. Number and percentage of I&M parks with each NRVA type

NRVA Type	# I&M Parks	% of I&M Parks (n = 289)
General assessment	41	14%
Broad-scale screen	283	98%
Systematic	127	44%
Single resource	34	12%
No NRVA	2	1%
Only broad-scale screen	118	41%
All 4 NRVA types	7	2%

There were some regional patterns in the distribution of NRVA types across parks (Figure 3-2). Excluding broad-scale screens, NRVAs have been conducted for most parks in the eastern U.S. (i.e., the Midwest, Northeast, National Capital, and Southeast regions) (Figure 3-2). Similarly, nearly 70% of island parks (Hawaii and Virgin Islands) have had at least one NRVA. Coverage was much lower in the Intermountain, Pacific West, and Alaska regions where only around 30% of parks have been evaluated by some form of NRVA outside broad-scale screens.

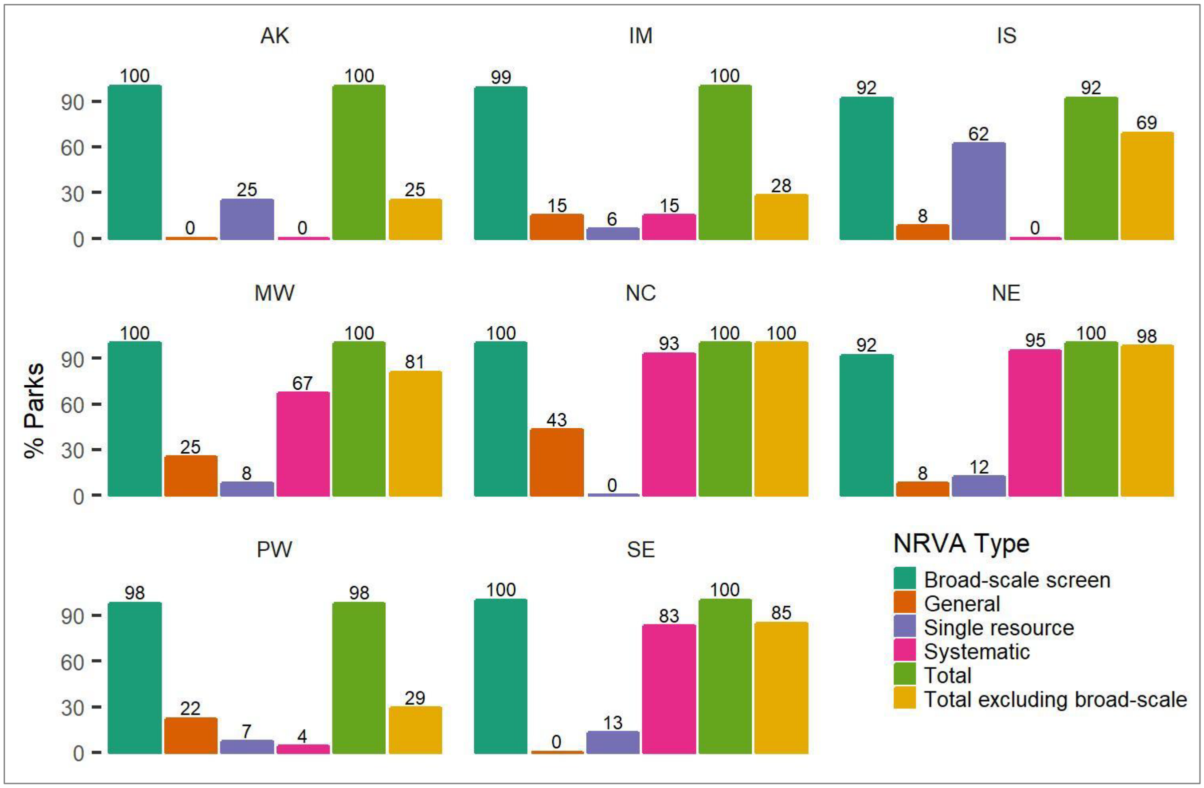

Figure 3-2. Percentage of parks in each geographic region with at least one existing explicit and/or implicit NRVA by type. Regions include AK (Alaska), IM (Intermountain), IS (Island parks on HI, PR, or VI), MW (Midwest), NC (National Capitol), NE (Northeast), PW (Pacific West excluding HI), and SE (Southeast).

The types of NRVAs conducted in each region differed as well. Systematic NRVAs were more prevalent in the eastern U.S. and accounted for nearly all NRVAs in the Southeast and Northeast regions. These systematic assessments focused solely on a single taxon, such as tree species. Most of the NRVAs conducted in the Alaska Region, Hawaii, and the Virgin Islands were single resource analyses (Figure 3-2).

Some individual parks have had many assessments. Parks with the most NRVAs included YELL (16 total NRVAs including broad-scale screens), GLAC (12), ACAD (10), GRTE, GRSM, and EVER (8).

Natural Resources Vulnerability Assessment Targets

General NRVAs were the most common NRVA type and these nearly always targeted a wide range of natural resources. At a minimum, general assessments included an overview description of projected physical climate changes as well as potential impacts on several different resource types. Consequently, assessments most frequently targeted multiple types of resources (35%, n = 25, Table 3-3). For example, Ashton (2010) evaluated species, habitats, and ecological properties (such as biodiversity) and processes (such as fire, connectivity, and phenology). Halofsky et al. (2011) evaluated road maintenance, fish habitat, vegetation change, and wildlife. Amberg et al. (2012) included five habitat types, three ecological processes, multiple species and taxonomic groups, and cultural resources.

Table 3-3. Vulnerability targets addressed in the NRVAs.

NRVA Target Category	NRVA Target	Count
Multi-target	–	25
Habitat/vegetation	Aquatic - Streams/rivers	2
	Desert habitats	1
	Everglades ecosystem	3
	Marine - Mangroves	1
	Marine - Salt marsh	1
	Category total	8
Process	Flood events	1
	Onset of early spring	1
	SLR	10
	Category total	12
Species	Birds	1
	Elk	1
	Mammals	1
	Meltwater stonefly	1
	Plants	6
	White pines	1
	Whitebark pine	2
	Endemic perennial herb	1
	Multi-taxa	4
	Category total	18

Table 3-3 (continued). Vulnerability targets addressed in the NRVAs.

NRVA Target Category	NRVA Target	Count
Other	Air quality	1
	Ecosystem services	1
	Glacier	2
	Physical climate	4
	Category total	8
Totals	**–**	**71**

Outside of general assessments, species were the most frequently assessed target (25%, n = 18), followed by SLR (14%, n = 10) and habitats or vegetation (11%, n = 8). All but three of the studies that assessed species assessed multiple species. Of the species studies focusing on plants, eight out of ten focused on tree species.

Components of Vulnerability

Vulnerability components include sensitivity, exposure, and adaptive capacity (Table 3-4). We restricted our analysis of vulnerability components to NRVAs that explicitly claimed to be evaluating vulnerability (n = 40). Of these explicit NRVAs, slightly less than half of the studies used the terms "exposure," "sensitivity" and/or "adaptive capacity" to describe aspects of their VA (Table 3-5). Exposure was the most frequently included term (n = 20), followed by sensitivity (n = 16), then adaptive capacity (n = 11). About a quarter of the explicit NRVAs directly addressed all three vulnerability components (n = 11), an additional four addressed exposure and sensitivity, and six addressed either sensitivity alone (n = 1) or exposure alone (n = 5). Many assessments used trait-based information about species' physiological tolerances or reliance on sensitive habitats to evaluate sensitivity (Amberg et al. 2012, Barrows et al. 2014). Most NRVAs used projected climatic conditions to evaluate exposure, but some used measures of historical climate change over time. Other NRVAs relied on climatic niche models to project potential range shifts for individual species. These models incorporate sensitivity by measuring the species' climatic niche and exposure by incorporating a range of projected future climate conditions (Hansen and Phillips 2015; Zolkos et al. 2015).

Although about half of explicit NRVAs did not use these specific terms, they all conceptually addressed sensitivity and exposure. Eight of the assessments that did not explicitly use these terms evaluated potential inundation from SLR using the Coastal Vulnerability Index (CVI; Pendleton et al. 2006). These assessments did not use the terms exposure or sensitivity, but included relative sea-level change, a potential measure of exposure, and characteristics such as coastal slope and geomorphology which can be interpreted as measures of a site's sensitivity to sea level changes (Pendleton et al. 2010).

Table 3-4. Examples of sensitivity, exposure, and adaptive capacity approaches.

Type	Sensitivity	Exposure	Adaptive Capacity
Direct (for sensitivity and exposure) or intrinsic (for adaptive capacity)	Physiological tolerances taken from the literature (Barrows et al. 2014; Ulrey et al. 2016)	Historical (Gonzalez et al. 2018) and projected changes in climate (Stroh et al. 2016). Projected sea-level rise (Pendleton et al. 2010). Projected changes in fire frequency or intensity (Panek et al. 2009).	Physiological tolerances taken from the literature (Barrows et al. 2014; Ulrey et al. 2016)
Indirect (for sensitivity and exposure) or extrinsic (for adaptive capacity)	Climatic niche model projections (Zolkos et al. 2015) Dynamic global vegetation model projections (Panek et al. 2009)	Climatic niche model projections (Fisichelli et al. 2014). Projected inundation from SLR. Coastal Vulnerability Index (Pendleton et al. 2010).	Surrounding land cover (Hansen et al. 2014; Stroh et al. 2016) Topography (Stroh et al. 2016)

Table 3-5. Number and percent of NRVAs that explicitly use the terms sensitivity, exposure, and/or adaptive capacity in a vulnerability context.

Vulnerability Terms	#	%
Sensitivity + Exposure + Adaptive Capacity	11	28%
Sensitivity + Exposure	4	10%
Sensitivity	1	3%
Exposure	5	13%
None	19	48%
Total	**40**	**100%**

Common Models & Assessment Tools

Most studies (79%, n = 56) used future climate model projections to assess vulnerability. Of the 15 studies that did not use climate projections, 9 evaluated coastal vulnerability to SLR, 3 used historical climate changes to measure vulnerability, 2 discussed climate changes in general terms, and the final one focused solely on sensitivity.

Studies employed a diversity of models to estimate potential future changes in resource conditions or levels, including hydrological models, climate models, species distribution models, and vegetation models (Table 3-6). Almost a third of studies (30%, n = 21) included range shift models, most commonly statistical, climatic-niche models. In addition to models, assessments often used existing VAs or tools (Table 3-7). Many studies (24%, n = 17) used some sort of vulnerability index. Of these, about half used the CVI and about half used a trait-based approach to evaluate species or habitat types.

Table 3-6. Models used to project potential climate impacts as part of NPS NRVAs.

Model	Purpose	Example Study
Sea, Lake, and Overland Surges from Hurricanes (SLOSH)	Estimate potential storm surge heights	Murdkheyeva et al. 2013
Sea Level Affecting Marshes Model (SLAMM)	Simulate long-term impacts of SLR on shorelines and wetlands	Murdkheyeva et al. 2013
General circulation models (GCMs)	Simulate the earth's climate (as future projections and historical reconstructions)	Gonzalez 2014
Species distribution models	Modeling current or potential future species distributions	Zolkos et al. 2015
Process-based vegetation models	Simulate vegetation distributions and responses to climate change	Gonzalez 2014
Variable infiltration capacity model (VIC)	Simulate hydrology and in particular projected impacts of climate change on water availability	Halofsky et al. 2017

Table 3-7. Vulnerability assessment tools and indices used in NPS climate change NRVAs.

Tool	Purpose	Example Study
Climate Change Vulnerability Index (CCVI)	Estimates relative vulnerability of species to climate change	Bruno et al. (2012)
Habitat Climate Change Vulnerability Index (HCCVI)	Provide a relative estimate of the vulnerability of habitats to climate change	Comer et al. (2012)
Coastal Vulnerability Index (CVI)	Assess the vulnerability of coastal land to SLR	Pendleton et al. (2006)
The NEAFWA regional habitat vulnerability model	Evaluate habitat and species vulnerability	Galbraith (2011) in Amberg et al. (2012)

Uncertainty

Most of the studies (89%, n = 63) addressed uncertainty in some way. Most studies that explicitly addressed uncertainty used multiple climate futures (i.e., two or more general circulation models (GCMs) and emission scenario combinations). A small number of studies engaged in a formal scenario planning process. These two approaches to addressing uncertainty are easily conflated because authors often use the term climate "scenario" to refer to these climate futures. To address this confusion, the NPS has adopted the term "climate futures" to refer to a range of projected climatic conditions resulting from different GCMs and/or emissions pathways (Lawrence et al. 2021; Runyon et al. 2020). These climate futures provide a quantitative upper and lower bound for potential changes. By contrast, scenario planning is a formal planning process that seeks to develop a series of alternative plausible scenarios that differ depending on one or more critical uncertainties. These scenarios are often informed by climate projections but are not direct projections themselves. Five NRVAs reviewed here described using a formal scenario planning process; three of these were in the Everglades (Catano et al. 2015; Flower et al. 2012; Koch et al. 2015) and two were in the Dakotas (Symstad et al. 2014; 2017). Since the time of this review, scenario planning has been implemented in Devil's Tower National Monument (Schuurman et al. 2019) and Wind Cave National Park (Runyon et al. 2021) and is increasingly a core strategy for evaluating climate change vulnerability used by the NPS Climate Change Response Program. Miller et al. (2022) provide a detailed description of climate change scenario planning for natural resources and its benefits. Of the studies that did not explicitly address uncertainty, one evaluated the presence of climate-sensitive aquatic species (Schwoerer and Dodd n.d.), and the remainder applied the CVI, which measures current coastal characteristics (e.g., Pendleton et al. 2010).

3.7 Best Practices

Consider the trade-offs across different NRVA types and select a NRVA approach that best meets the management needs of the park and the resources available. Even a rapid and comparatively superficial NRVA can help managers begin to incorporate climate impacts into their management planning. Conversely, developing a complex model for a single species has limited applicability to other resources, but may be necessary to manage certain priority species effectively.

In general, we found trade-offs between the conceptual or spatial scope of the assessment and its comprehensiveness and detail (Figure 3-3). Assessments that focused on a single type of resource can include more detailed information and tailor-made models to project changes in the magnitude and spatial distribution of impacts. By contrast, general assessments that evaluate vulnerability more broadly rely heavily on existing knowledge, publications, data, or models. Vulnerability assessments that focus on a single park, or regional cluster of similar parks, have the capacity to account for local or regional dynamics and conditions as opposed to broad-scale assessments.

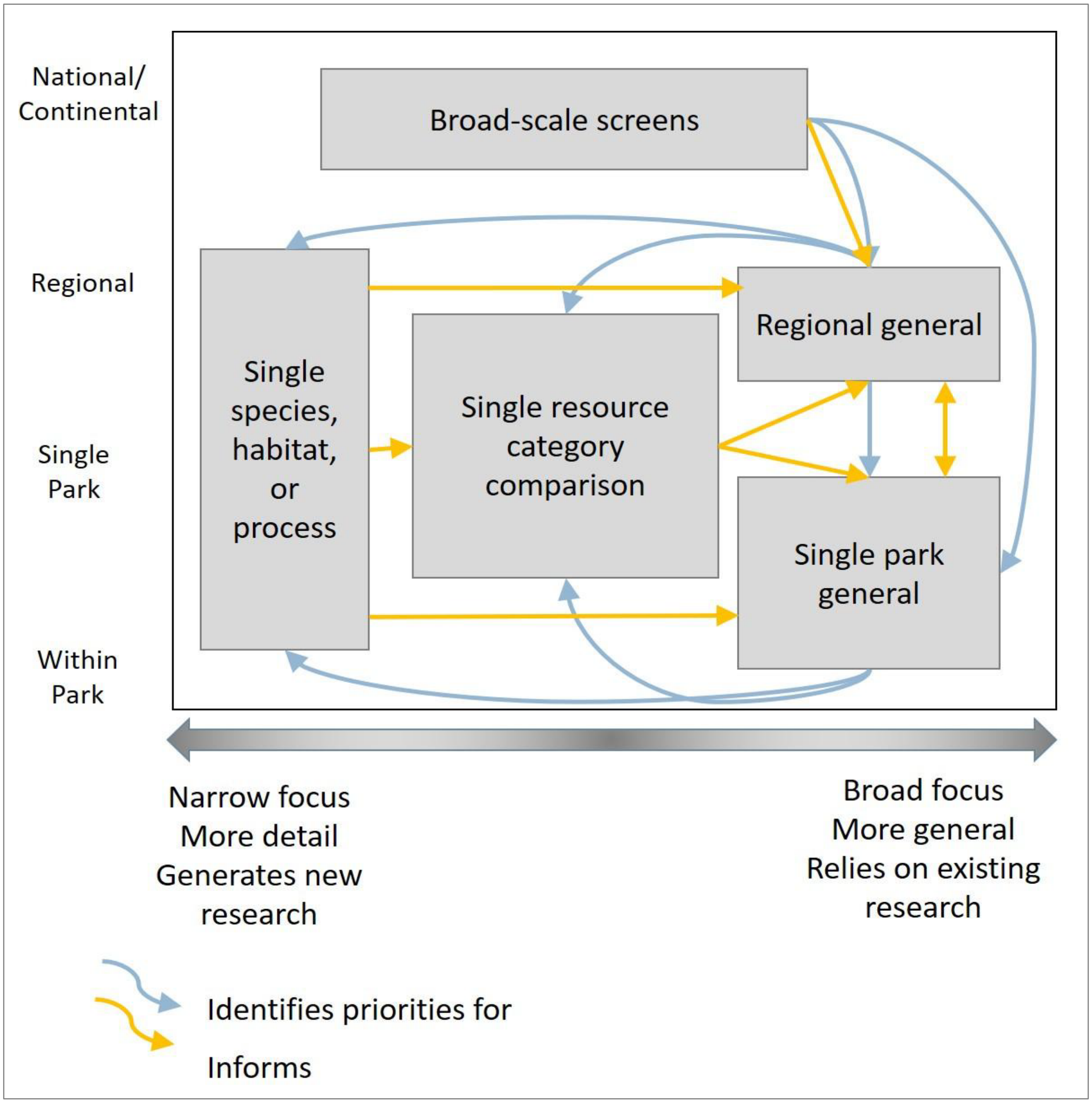

Figure 3-3. Conceptual diagram of NRVA types illustrating trade-offs between conceptual scope and spatial scale and how different types of NRVAs relate to one another.

Given these trade-offs, each of these assessment approaches has a different role to play in contributing to the overall understanding of climate change vulnerability across the NPS (Figure 3-3). National-level assessments that use consistent datasets to evaluate numerous parks provide a relative, though incomplete, assessment of vulnerability across numerous parks (Hansen et al. 2014). These types of analyses can rapidly quantify widespread climate change vulnerabilities if broad-scale data are available (Monahan et al. 2016; Val Martin et al. 2015; Wu et al. 2018). Calculating broad-scale vulnerability metrics for multiple parks simultaneously can be an efficient way to provide information to managers developing park specific assessments. However, it is important to remember that assessments with a large spatial extent will miss important local and regional impacts. They particularly have a limited capacity to identify local sensitivities and link them directly with relevant exposures. As a result, these assessments do not replace, but rather can inform local and regional NRVAs.

A general climate change vulnerability analysis of a single or small cluster of park units starts with a broad assessment of both potential climate exposures and key resources or park values. General assessments ideally incorporate all key climate impacts and priority resources, although the scope must be limited. These kinds of assessments rely on gathering and synthesizing existing information as well as using expert knowledge to identify potential links between expected climate exposures, resource sensitivities, and adaptive capacities. These assessments are particularly useful for identifying and prioritizing key vulnerabilities and interactions across multiple vulnerabilities that require more specific modeling. In addition, they can provide a road map for adaptation planning which may include identifying needs for further modeling and research (Halofsky et al. 2011).

Finally, more specialized assessments focus on either one process, like SLR, or resource, like one or more individual species or habitat types. Even these more specialized assessments face the same trade-off between breadth and depth. Rapid trait-based assessment methods like the NatureServe CCVI (Young et al. 2015), can be applied to many species or habitats relatively quickly. Yet checklist approaches can miss important aspects of vulnerability, struggle to calculate threshold or net vulnerability when different traits have different vulnerability implications, and rarely provide spatially explicit results. Simple climatic niche models can also be applied relatively rapidly across multiple species but fail to account for important behavioral and ecological species traits. In short, rapid assessment approaches can provide important information for many species or habitats relatively quickly, but each one has important limitations that need to be considered (Dawson et al. 2011; Michalak et al. 2017; Rowland et al. 2011). By comparing multiple data sources and projections, it is possible to take advantage of the strengths of the different approaches while making up for the weaknesses in others, thereby building more robust assessments of vulnerabilities (Michalak et al. 2017).

We found that nearly all the I&M parks have been included in at least one NRVA to date. However, only 8% of I&M parks have been the subject of a comprehensive, general NRVA that provides a detailed overview of key impacts and vulnerabilities for that park. An additional 39% of parks have been evaluated by a systematic NRVA. Systematic NRVAs have a somewhat broader scope compared to broad-scale or single resource assessments as they tend to cover numerous species and habitats. However, these assessments generally use a single, relatively rapid methodology, such as trait-based index or range-shift models, which when used in isolation, miss unique aspects of vulnerability particular to specific species or habitats. In addition, systematic NRVAs do not include more general information about climate impacts and so are less relevant to sectors outside natural resources. In some cases, a park has not been evaluated by a single general analysis, but rather by several NRVAs that either focus on a single or group of resources. For example, ACAD has not been evaluated by an in-depth general assessment, but has had multiple NRVAs that could be synthesized into a detailed general NRVA relatively rapidly.

Over half of the parks have only been included in NRVAs with comparatively narrow conceptual scopes. Nearly half of the parks have only been the subject of a broad-scale assessment. Broad-scale assessments provided very limited vulnerability information because they typically address a narrow subset of vulnerabilities (e.g., air pollution, early onset of spring, or exposure) and rely on broad-scale datasets that may have inaccuracies at the individual park scale. An additional 6% of parks have only been evaluated by a single species or process NRVA, which, by definition, have a very narrow conceptual scope.

Ultimately, implementing multiple assessments may be most effective to fully understand vulnerability. For example, a general NRVA can synthesize existing information, integrate multiple VA approaches, and identify key vulnerabilities. However, general NRVAs are unlikely to include enough detailed, quantitative information to develop management plans for individual species or resources. By contrast, single-resource assessments have a very narrow scope, but can develop detailed models that can be more informative for setting management targets.

Conduct regional NRVAs for groups of parks with similar climatic and ecological characteristics. Each park unit is unique, but at a broad level, parks within the same region are more likely to face similar climate impacts. Here we use the term "region" to describe a group of parks that share a similar geography, as opposed to officially designated regional boundaries. The similarities will obviously be greater for parks sharing similar types of habitats and other natural resources. For example, Saunders et al. (2011) evaluated potential for "climate disruption" across 5 parks in the Great Lakes region. This included a discussion of the potential climate changes unique to parks along the shoreline of the Great Lakes as well as impacts to wildlife and habitats common to that geography. These included the lake environment itself, inland waters and wetlands, and shoreline forests. Finally, the report also evaluated potential impacts to recreation including changes in fishing, boating, and public health and associated economic impacts. Similarly, Ashton et al. (2010) synthesized existing literature on potential climate impacts to 11 parks in the Rocky Mountain and upper Columbia Basin, including summaries of impacts to region-specific resources such as aspen and alpine communities, as well as regional phenomena such as wildlife connectivity. By contrast, Stroh et al. (2016) used a series of metrics to evaluate 60 parks in the Midwest Region. The metrics addressed different aspects of sensitivity, exposure, and adaptive capacity. However, the metrics themselves were not region-specific and did not address region-specific habitats or species. As a result, although this analysis provides information about the relative vulnerability of each park, it is less informative for resource management.

The regional NRVAs being conducted by the Adaptation Partners project (http://adaptationpartners.org/) are an excellent example of developing partnerships across multiple land management units and agencies in a single region. Regional partnerships can leverage resources to provide in-depth vulnerability and adaptation information to a diversity of land managers. At the time of writing, this effort had produced two final reports covering 3 National Parks (OLYM - Halofsky et al. 2011; MORA and NOCA - Raymond et al. 2014) and an additional report for south central Oregon, including CRLA, is in the final draft stages (Halofsky et al. 2019).

Design NRVAs so that they are easily updated and applicable to a wide range of natural resources and other sectors. It is not possible for any single NRVA to truly address all important park resources and values. However, some types of NRVAs are more flexible, easier to update, and more applicable to a wide range of resource types. General NRVAs that provide a detailed description of expected climate impacts can inform management decisions for a wide range of natural resources and even other sectors. As a result, general NRVAs can be relevant to a broad range of resources, even if those resources are not directly evaluated in the NRVA initially. By contrast, systematic or single resource assessments generally focus narrowly on the vulnerabilities of targeted natural resources making the information more difficult to transfer to resources that are not directly included in the NRVA.

When possible, use multiple tools and data sets. If the results from these different analyses and inputs are similar, one can be more confident in the conclusions drawn. If the results differ, the outputs can be used as complementary pieces of evidence. Having a solid understanding of the tools and datasets will facilitate a meaningful interpretation of divergent results. In the absence of adequate time or funding, a single tool or data set is better than none, if the limitations are acknowledged.

Different approaches to assessing vulnerability have been found to produce substantially different results (Lankford et al. 2014). Therefore, assessments that combine approaches are likely to be more robust than assessments that rely on an individual approach (Pacifici et al. 2015). One approach to integration involves combining different types of models (Case and Lawler 2017; Keith et al. 2008). Most general NRVAs reviewed here evaluated a wide range of evidence for potential impacts including field data, vegetation and range shift models, trait-based indices, and expert opinion (Halofsky et al. 2011; Raymond et al. 2014). By comparing multiple data sources and projections, it is possible to take advantage of the strengths of the different approaches while making up for the weaknesses in others, thereby building more robust assessments of vulnerabilities (Michalak et al. 2017).

Draw on existing datasets when possible. An expanding array of datasets are available at national or regional scales that can inform climate VAs including modeled projections of direct and derived climate variables, species range shifts, vegetation changes, and fire regime characteristics. Using existing data reduces costs, but must also be done with a clear understanding of the limitations associated with each dataset and existing datasets may not always meet the needs of individual parks.

About 40% of the NRVAs relied solely on existing data and literature. These were primarily general NRVAs that synthesized existing literature to identify potential vulnerabilities and systematic assessments that used a trait-based framework to estimate vulnerability. Some NRVAs generated new data through modeling efforts or data collection (Fisichelli et al. 2013; Monahan et al. 2016; Shovic and Thoma 2011), but many were able to evaluate existing climatic niche models, vegetation change projections (Gonzalez 2016), or existing projected shifts in species distributions (Zolkos et al. 2015). Still others synthesized data from past field studies (Munson et al. 2015) or gleaned species trait data or other information on vulnerability from the literature (e.g., Barrows et al. 2014). Some assessments summarized the results of past studies done in the park or in the region (e.g., Gonzalez 2014). With the growing availability of climate data and bioclimatic model projections, it should be getting progressively easier and cheaper to put together reliable climate change VAs using existing regional and local data sources.

Evaluate multiple components of vulnerability—ideally sensitivity, exposure, and adaptive capacity. Use known sensitivities to select exposure elements and aspects of adaptive capacity to explore. Ideally, VAs will evaluate all three components of vulnerability (Glick et al. 2011). An incomplete assessment has the potential to provide inaccurate or misleading results. For example, targets that will be exposed to large changes in climate may not be as vulnerable if they are not sensitive or if they have high adaptive capacity. That said, no assessment will be able to evaluate every aspect of sensitivity, exposure, and adaptive capacity. Of the three components of vulnerability, adaptive capacity has historically been the least understood, as evidenced by the relatively small percentage of the studies reviewed here that evaluated adaptive capacity. However, new approaches, tools, and guidance for evaluating adaptive capacity are available that can help managers address this critical component (Cook et al. 2021; Thurman et al. 2020; 2021).

Consider both intrinsic and extrinsic elements of adaptive capacity. Beever et al. (2016) described two kinds of adaptive capacity: fundamental and realized. Fundamental adaptive capacity is driven by intrinsic factors and realized adaptive capacity is fundamental adaptive capacity as modified by external factors. Intrinsic factors can include traits such as dispersal ability, phenotypic plasticity, or evolutionary potential (Foden et al. 2018). External factors can include the degree to which the surrounding landscape is fragmented or dominated by human activities. Species in highly fragmented landscapes may have trouble moving to track shifting climates. Similarly, coastal ecosystems bulkheaded by development will be unable to shift inland in response to rising sea levels.

Assess and document uncertainty in the assessment results and conclusions. Given the inability to accurately assess all aspects of sensitivity, exposure, and adaptive capacity of any assessment target, there will always be some uncertainty in VAs (Patt et al. 2005). In general, reviewing and comparing results from different approaches and models can help identify consensus or known uncertainties around future climate-induced changes (Michalak et al. 2017). Formal scenario planning is an effective approach to planning for uncertainty (Lawrence et al. 2021; Peterson et al. 2003; Runyon et al. 2020; Star et al. 2016) and Miller et al. (2022) provides guidance for implementing this approach in the context of NPS natural resource assessments. A more basic and rapid approach to addressing uncertainty is to evaluate multiple climate-change futures. These can be different model projections or different emissions trajectories. Likewise, there are approaches for assessing uncertainty in expert opinion (DeGroot 1988; Johnson and Gillingham 2004).

Think beyond assessing vulnerability and identify climate adaptation actions. Climate change is progressing rapidly (Allen et al. 2018), and impacts are already affecting parks (Gonzalez 2017). Evaluating climate change vulnerability is important but is only the first step in developing climate change-informed management plans. Several NRVAs included a discussion of potential climate change adaptation actions. The OLYM NRVA conducted by Halofsky et al. (2011) was explicitly designed to identify adaptation strategies. Saunders et al. (2011) included a brief discussion of strategies and actions that could help mitigate or reduce climate impacts. Vulnerability assessments need to be embedded within a broader effort to identify adaptation strategies and actions. Often, planners and managers may see VAs as the first step followed by adaptation planning. However, delaying the development of adaptation actions could leave managers unprepared for impacts that are already being felt and are projected to increase in the near term. Ensuring that adaptation planning is considered throughout the VA process can help park managers incorporate climate change into their planning and minimize climate impacts on the resources that parks are charged with protecting.

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Chapter 4: A Review of Vulnerability Assessments for Cultural Resources of the National Park Service

Pei-Lin Yu[1], Marcy Rockman[2], Connor Neal[1]

[1]Boise State University
Department of Anthropology
1910 University Blvd.
Boise, ID 87125

[2]National Park Service
Climate Change Adaptation, Cultural Resources
1849 C St. NW
Washington, D.C. 20240

Rock cairn and burial structure locations near sea level, Kalaupapa National Historical Park. (©PEI-LIN YU)

Please cite this chapter as:

Yu, P., M. Rockman, and C. Neal. 2022. Chapter 4: A review of vulnerability assessments for cultural resources of the NPS. Pages 94-132 *in* Peek, K.M., B. R. Tormey, H.L. Thompson, A. C. Ellsworth, and C.H. Hoffman (editors). 2022. Climate change vulnerability assessments in the National Park Service: An integrated review for infrastructure, natural resources, and cultural resources. Natural Resource Report NPS/NRSS/CCRP/NRR—2022/2404. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/nrr- 2293650.

4.0 Executive Summary

Across America, the National Park Service has conducted an array of vulnerability assessments for climate change impacts for the cultural heritage resources under National Park Service management, including archeological sites, historic structures, cultural landscapes, national historic landmarks, and more. Fourteen vulnerability assessments and supporting data were developed by the National Park Service and partners as of Spring 2018 (Appendix G). This report describes and compares the results of these assessments and whether the reports accomplished their objectives. The study was initiated in 2017 in partnership with Boise State University to summarize general characteristics and themes, identify gaps and opportunities, highlight approaches considered as best practices and illustrative case studies eligible to be included in the NP Adapt Database, and offer recommendations for future vulnerability assessment development, coordination, and access by parks and researchers. The goal of this project is to improve the practice of vulnerability assessments for cultural resources as well as scientific understanding of cultural resources vulnerability to climate change. The report found that the 14 cultural resources vulnerability assessments were largely successful in meeting their objectives. Seven actions are recommended in the near-term to build on current progress.

1. The National Park Service needs to implement data-sharing such as a centralized and secure reports "clearing house" for cultural resources vulnerability researchers. Future research scopes of work should include data sharing as part of deliverables, and this analysis should be updated every three to five years to incorporate vulnerability assessment projects already in planning and or under revision.
2. The definition and usage of key vulnerability concepts and terms for cultural resources can be simplified and made consistent. The following are proposed working definitions.
    a. Exposure is the degree to which a given resource is expected to experience or be subject to a climate-driven stressor, threat, or hazard.
    b. Sensitivity measures a resource's susceptibility to harm from exposure to a climate-driven stressor, threat, or hazard.
    c. Vulnerability is the sum of exposure and sensitivity.
    d. Adaptive Capacity measures the ability of human managers and systems to adjust the use and management of a given resource, and with cultural resources adaptive capacity should be addressed separately.[3]
3. The cultural resources vulnerability assessments should be considered in an integrated fashion with natural resources and facilities. This is feasible at park, cluster, regional, and national scales (extent). The incorporation of this report with others is an example of this integrated approach.

[3] Also see Box 1-1, and 1-2 in Chapter 1. Some organizations consider the potential response of managers to be part of adaptive capacity for a particular (non-living) resource or asset. Others consider such management response as *climate change adaptation*, and consider adaptive capacity only as the <u>inherent</u> ability of a resource or asset to independently adjust to climate change.

4. Researchers and National Park Service managers alike have pointed out a lack of subject matter expertise in integrating natural and cultural resources and facilities, and insufficient project time to dedicate to a focused, collaborative process. The shortage of dedicated time for cultural resources vulnerability assessments may be partly offset by incorporating external partners, but gaps may remain for park personnel participation. Strategic planning that maximizes support for and results from park personnel efforts and minimizes impacts to their workload should be included in vulnerability assessment scopes of work.
5. Incorporating vulnerability assessment concepts and methods into appropriate cultural heritage educational materials will build on collective progress for the benefit of future cultural heritage experts. The National Park Service already has strong partnerships with institutions of higher education and non-profit research organizations in this regard.
6. Ethnographic resources, sometimes termed "intangible heritage," are also highly impacted by climate change and deserve vulnerability analysis separately as well as in a supporting role for tangible cultural resources. The National Park Service ethnographic overviews and assessments, where available, as well as local community involvement in scoping, should be a part of all cultural resources vulnerability assessments.
7. Since this study was conducted in 2017-18, several of the near-term recommendations have been scoped or initiated at some National Park Service units in partnership with research institutions. Updating this study periodically will offer quantified metrics for accomplishments in recommendations and desired outcomes, and gaps that persist or emerge.

4.1 Acknowledgments

Special thanks are extended to the National Park Service for leadership and guidance on cultural resources vulnerability assessments. Our gratitude to park staff, partners and stakeholders, and members of the academic community whose extraordinary efforts and expertise contributed to the creation of these reports. We wish particularly to acknowledge the contributions of Native and Indigenous holders of cultural heritage values and knowledge. This body of work provides the NPS and others with a strong foundation for improving our understanding of cultural resource vulnerability, and a better future for America's cultural heritage resources. Appreciation is also extended to the Rocky Mountains Cooperative Ecosystem Studies Unit for facilitating this agreement, and to the Grants and Agreements staff at the National Park Service, and Boise State University's Office of Sponsored Programs and College of Arts and Sciences for helping the project to stay on time, task, and budget. This project was funded by the NPS Climate Change Response Program. Please note that this report reflects citations and the state of knowledge as of Spring 2018.

4.2 Acronyms

CRVA: Cultural Resources Vulnerability Assessment

FMSS: Facilities Management Systems Software (NPS)

GIS: Geographic Information Systems

NHL: National Historic Landmark

NPS: National Park Service

CCRP: Climate Change Response Program (NPS)

POSE: Physical, Organizational, Social, and Economic

SDM: Structured Decision Making

SLR: Sea-Level Rise

VA: Vulnerability Assessment

4.3 NPS Region and Unit Codes

Region Codes

AKR: Alaska Region

IMR: Intermountain Region

MWR: Midwest Region

NER: Northeast Region

PWR: Pacific West Region

SER: Southeast Region

Park Unit Codes

BADL: Badlands National Park

CAHA: Cape Hatteras National Seashore

CALO: Cape Lookout National Seashore

COLO: Colonial National Historical Park

DEVA: Death Valley National Park

EUON: Eugene O'Neill National Historic Site

GATE: Gateway National Recreation Area

GWMP: George Washington Memorial Parkway

NEPE: Nez Perce National Historical Park

NOCA: North Cascades National Park

PORE: Point Reyes National Seashore

PUHE: Pu'ukoholā Heiau National Historic Site

REDW: Redwood National and State Parks

SAGA: Saint-Gaudens National Historical Park

SHEN: Shenandoah National Park

VAFO: Valley Forge National Historical Park

4.4 Introduction

The five categories of cultural resources that are managed by the National Park Service (NPS; archeological sites, pre-contact and historic buildings and structures, cultural landscapes, ethnographic resources, and museum collections/archives) have always been affected by environmental forces. Over the past decade, data and observations from across the U.S. National Park System signal that these forces are accelerating, intensifying, recombining, or being joined by new forces (Caffrey et al. 2018; Rockman et al. 2016) as a result of changing climate. The NPS currently projects that each of its units, which stretch from Maine to Alaska and from the Caribbean to American Samoa, are being or will be affected by climate change in some way (Rockman et al. 2016; National Park Service 2012; 2014a).

This impacts the mission of the NPS. In 1916, the passage of the Organic Act charged the NPS to "preserve unimpaired" the resources of the parks for future generations. Through much of the 20th century, "unimpaired" with respect to cultural resources has been generally interpreted as "unchanging," but emerging climate change related impacts to the integrity of park resources, and associated changes to policy and guidance, are now challenging the "unchanging" reading of the unimpaired concept (see Colwell et al. 2012). The NPS created the Climate Change Response Program (CCRP) in 2009 and subsequently developed a family of NPS strategic documents that further support coordinated climate change response. These include to date: Climate Change Response Strategy (2010), Climate Change Action Plan 2012-2014 (2012), Green Parks Plan (2012), Using Scenarios to Explore Climate Change: A Handbook for Practitioners (2013), the NPS Cultural Resources Climate Change Strategy (2016), and Sea-Level Rise and Storm Surge Projections for the National Park Service (2018). In addition, then-NPS Director Jon Jarvis issued a series of policy memoranda on this subject to address management policies (PM 12-02), cultural resources (PM 14-02), and facilities (PM 15-01).

With regard to cultural resources, Goal 7 of the NPS Climate Change Response Strategy (2012) calls for the agency to "develop, prioritize, and implement management strategies to preserve climate-sensitive cultural resources." In 2014, NPS Policy Memorandum 14-02, "Climate Change and Cultural Resources" reaffirmed the principle of prioritizing limited cultural resource funding and management support. According to this memorandum, project design must evaluate cultural resources in terms of their vulnerability and significance to ensure that "management decisions are directed to resources that are both significant and most at risk" (Ibid).

Documenting the vulnerability of resources to climate change is central to a scientifically sound, transparent, and replicable method to prioritize actions to protect resources under threat of climate change impacts (National Park Service 2014a). Vulnerability assessments (VAs) are one method to "quantify the potential responses of plants, animals, cultural resources, and infrastructure to increasing temperatures, sea-level rise, range shifts, extreme events, and other climate change impacts. They identify vulnerable areas and potential refugia, providing key information to *prioritize areas* for climate adaptation measures" (National Park Service 2016; p. 1, emphasis added). Rockman et al. (2016) describe the role of VAs as "connecting *exposure* to climate impacts with resource-specific *sensitivities* to determine impact risk at site-specific and regional scales" (p. 10, emphasis added).

NPS Policy Memorandum 14-02 directs resource managers conducting VAs to focus on the most vulnerable and significant cultural resources. Since 2009, vulnerability assessment (VA) studies have taken on the task of determining risk to park resources – natural, cultural, facilities/infrastructure, or integrated approaches – for climate impacts. Several VA reports for cultural resources were developed or in some cases completed before key pieces of cultural resources climate change guidance were completed (NPS 2014a; Rockman et al. 2016). For this reason, several reports assessed in this study do not match current NPS guidance on VAs. However, they remain valuable as examples of how to gather, analyze, and present relevant vulnerability information.

To build on prior work and avoid unnecessary duplication, parks, partners, and decision-makers need to be able to incorporate completed VAs into their current and future work. The NPS is a largely decentralized agency that provides policy, guidance, and coordination to enable the managers of over 400 individual park units to address site-specific issues and conditions in a consistent manner across the service. This has allowed different sectors to test methods of assessing vulnerability for different types of cultural resources and management questions. Periodic synthesis and evaluation of results enables identification of best management practices to determine which VA method or set of methods is most effective and should be most widely adopted.

The NPS now faces the following challenges: 1) cultural resources vulnerability assessment (CRVA) products (reports, publications, summaries, etc.) are archived in multiple locations in varied formats. These products are not readily discovered nor acquired, and 2) analysis of gaps and best practices of the aggregate of these reports has not been conducted. These challenges present obstacles to investigators, subject matter experts, and agency decision-makers to conduct VAs in an informed manner. As a result, new VAs are proceeding without the benefit of knowledge gained from prior efforts.

The purpose of this project is to improve the state of knowledge about CRVAs through actions to meet the above challenges. These actions include: 1) summarizing general characteristics and themes in the NPS CRVA reports, 2) identifying lessons learned and gaps that still need to be addressed, 3) highlighting approaches considered as best practices and illustrative case studies eligible to be included in the NP Adapt Database, 4) recommending best practices for CRVAs to inform the design and implementation of future efforts.

This project contributes to a nationwide initiative to inventory and assess climate change VAs for NPS natural and cultural resources and facilities. The results of this study will integrate cultural resources climate change vulnerability information into that broader multidisciplinary effort.

Cultural Resources Vulnerability Assessments

The universe of NPS CRVAs as of Spring 2018 is small, yet diverse. Fourteen NPS VAs that focus on cultural resources or incorporate them in multi-disciplinary assessments were selected for this study (Table 4-1, and Figure 4-1). More are underway or in planning stages.

Table 4-1. NPS CRVA reports reviewed as of April 2018.

Report(s)	Title
Amberg et al. 2012	Badlands National Park Climate Change Vulnerability Assessment
Newland 2013	The Potential Effects of Climate Change on Cultural Resources Within Point Reyes National Seashore, Marin County, CA
Wilson 2014	Assessment of National Park Service Museum Facilities' Vulnerability to Climate Change
National Park Service 2014b; c; Nersesian and Ehler 2015	Gateway National Recreation Area General Management Plan Appendix B: Gateway National Recreation Area General Management Plan Superstorms, Shutdowns, and the Future of Cultural Resources: Gateway National Recreation Area: A Case Study
Peek et al. 2015	Adapting to Climate Change in Coastal Parks: Estimating the Exposure of Park Assets to 1 m of Sea-Level Rise
Melnick et al. 2015	Climate Change and Cultural Landscapes: Research, Planning, and Stewardship
Anderson 2016	Northern Alaska National Historic Landmark Condition and Vulnerability Assessment Project
Stein-Espanola, in draft	Cultural Resource Climate Change Assessments of National Historic Landmarks in the Pacific Island Network of the National Park Service (in draft)
Melnick et al. 2016a; b	Study of Climate Change Impacts on Cultural Landscapes in the Pacific West Region, National Park Service Study of Climate Change Impacts on Cultural Landscapes in the Pacific West Region (desktop assessment method)
Melnick et al. 2017	Study of Climate Change Impacts on Cultural Landscapes in the Pacific West Region, National Park Service Phase II: Preliminary Vulnerability Assessments
Fatorić and Seekamp 2016; 2017	2016. Assessing Historical Significance and Use Potential of Buildings within Historic Districts: An Overview of a Measurement Framework Developed for Climate Adaptation Planning 2017. Connecting Landscape Adaptation and National Cultural Resource Policy to Climate Change and Cultural Resource Adaptation Decisions
Allen 2017	Identify Cultural Resources Sites Affected by SLR at Cape Hatteras National Seashore
Ricci et al. 2019b	Method for Integrated Coastal Climate Change Vulnerability Assessment

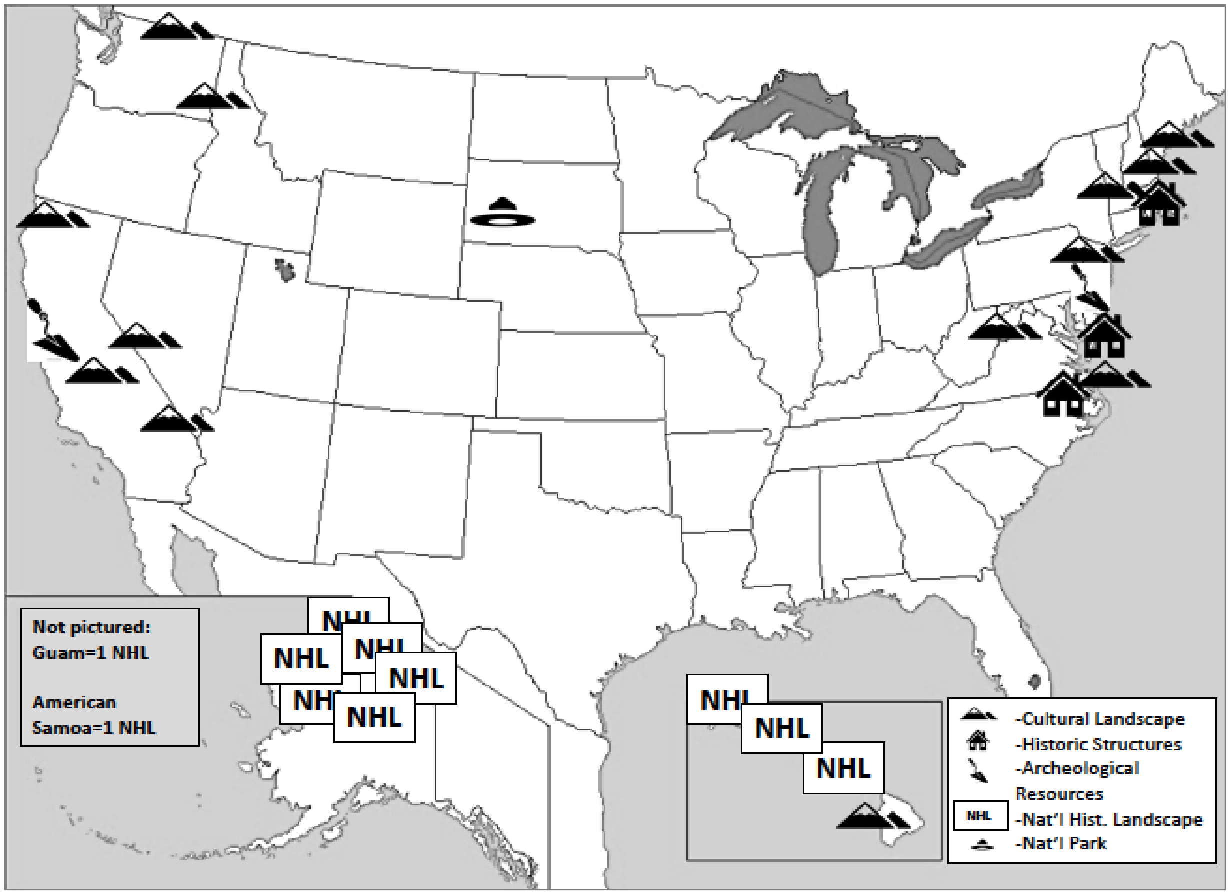

Figure 4-1. Map of NPS climate change CRVAs included in this review, as of April 2018. Large-scale and nation-wide studies are not included on this map.

Summary information by region (Table 4-2 and Figure 4-2) indicates that coastal and island park units (in the Northeast, Southeast, Pacific West, and Alaska regions) are leading in VA efforts. Additional work includes two nationwide assessments for coastal and museum resources, and three inland assessments: an integrated effort for a park unit in the Midwest Region (MWR) and assessments for cultural landscapes in the Northeast Region (NER) and Pacific-West Region (PWR)

In an example from the Intermountain Region (IMR; Jeffery and Burghardt 2014), VA models and methods for Vanishing Treasures structures were reviewed at the regional landscape scale (extent). The Vanishing Treasures effort is not yet complete, so it was not assessed in this study, yet stands out for its regional scale (extent) and evaluation of VA methodologies. Exposure, sensitivity, and other key terms and concepts were included in the report, which represents Phase I. The Phase II effort, underway at the time of this writing, is assessing vulnerability at the park scale (extent) to inform management decisions.

Table 4-2. NPS CRVA report characteristics.

Report(s)	Cultural Resource Assessed	Region	Scale (Extent) of Analysis
Amberg et al. 2012	National Park	MWR	One park unit (BADL)
Newland 2013	National Seashore	PWR	One national seashore (PORE)
Wilson 2014	Museum Facilities	All	Nationwide: all seven regions
National Park Service 2014b; c; Nersesian and Ehler 2015	National Recreation Area	NER	Three park units of GATE
Peek et al. 2015	Coastal Parks	All	40 coastal park units, east and west
Melnick et al. 2015	Cultural Landscapes	NER	Six cultural landscapes (CALO, GATE, SHEN, SAGA, GWMP, and VAFO)
Anderson 2016	National Historic Landmarks	AKR	Six National Historic Landmarks
Stein-Espanola, in draft	National Historic Landmarks	PWR	45 National Historic Landmarks
Melnick et al. 2016a; b	Cultural Landscapes	PWR	Six cultural landscapes, two reports (REDW, DEVA, PUHE, NOCA, EUON, NEPE)
Melnick et al. 2017	Cultural Landscapes	PWR	Three cultural landscapes (REDW, NOCA, DEVA)
Fatorić and Seekamp 2016; 2017	National Seashore	SER	One national seashore (CALO)
Allen 2017	National Seashore	SER	One national seashore (CAHA)
Ricci et al. 2019a	National Historical Park	NER	One national park unit (COLO)

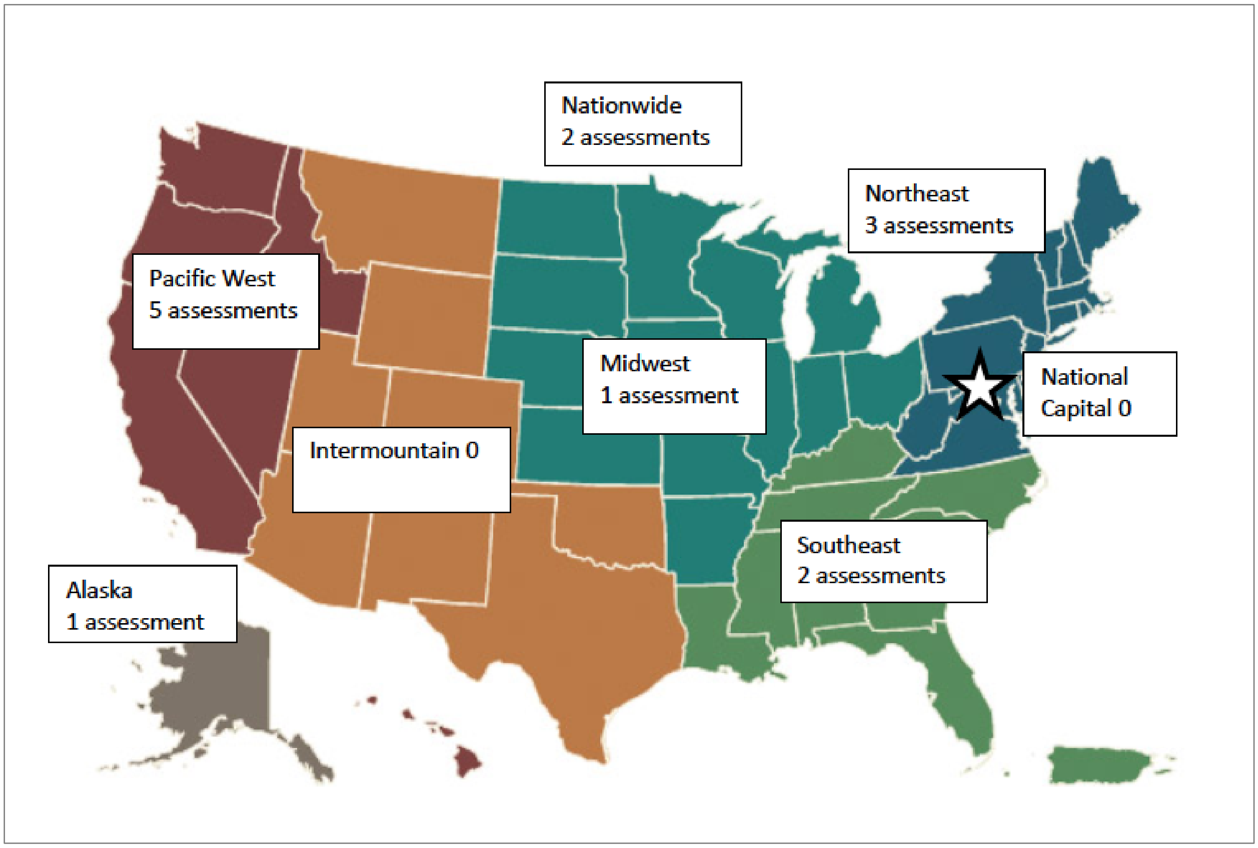

Figure 4-2. Map distribution of climate change CRVAs by NPS region, as of April 2018. Large-scale and nation-wide studies are not included on this map.

4.5 Methods

Reports and data tables used in this study were selected by the NPS cultural resources program of the NPS CCRP office in June 2017. Final versions were substituted if a report changed from draft to final during the study period. Newly available materials were added until Spring 2018. Due to the diversity and small number of the NPS CRVA reports, the analysis was qualitative in nature. Data were recorded in narrative form in MS Word, and in summary form in a MS Excel spreadsheet. Summary data included background information on management history and goals; definitions and usages of key terms; report outcomes; and recommendations. An evaluation rubric was used to ensure consistency in gathering, structuring, and analyzing the data (see Appendix F). Telephone interviews were conducted with selected NPS personnel to gain insight into outcomes, gaps, and recommendations. Conference calls and section reviews between co-authors allowed course adjustments and updates throughout the process.

4.6 Data and Results

The following section describes CRVA report management objectives, broad and over-arching themes, compares the ways that key concepts such as exposure, sensitivity, and vulnerability were used, and scopes the most effective approaches to inform future efforts in CRVAs.

Objectives and Goals of Cultural Resources Vulnerability Assessments

The reports share the general goal of assessing climate vulnerability of cultural resources under NPS stewardship, but objectives vary according to characteristics of the unit or units studied, the scale (extent) and nature of cultural resources considered, the priorities of the NPS, and expertise areas of the researchers. In addition, later assessments have benefitted from the accomplishments and lessons learned in earlier efforts.

Management goals and objectives for the NPS CRVAs varied in scale (extent) from individual park units to nationwide assessments, and in scope, varying from specific cultural resource types such as indigenous archeological sites to integrated assessments covering natural, cultural, and facilities resources. The intended outcomes covered the spectrum from detailed listings and descriptions of threats and impacts to assessments of resource sensitivity to recommendations for adaptive measures. Methods ranged from desktop assessment of remote sensing and Geographic Information Systems (GIS) data, to hands-on consultations with stakeholders and field visits to collect fine-grained information, and several reports presented methodologies as pilot studies. Table 4-3 presents abbreviated management objectives and goals for each report or set of reports.

Short summary narratives to support Table 4-3 are presented below for each report or set of reports in chronological order.

Table 4-3. Abbreviated management objectives and goals of NPS CRVA reports.

Report(s)/Focus	Study Objectives & Goals
Amberg et al. 2012/BADL	Conduct an integrated natural and cultural resources assessment for BADL; provide template and guidelines for other NPS units. Includes ethnography and brief section on archeology.
Newland 2013/PORE	Compile evidence for climate change threats to 88 indigenous archeological sites at PORE, describe the threats, rank sites in order of threat level, propose options for minimizing and mitigating for impacts.
Wilson 2014/Museums	Gather data on climate change natural hazard risks to museum facilities for all regions of the NPS.
Nersesian and Ehler 2015; NPS 2014b; c/GATE	Develop a process for prioritizing historic structures at GATE for protective and mitigation actions, as part of a larger resource management plan.
Peek et al. 2015/Coastal	Predict exposure of cultural and historic facilities including buildings, to one meter of SLR across 40 coastal parks.
Melnick et al 2015/E. Cultural Landscapes	Develop a method for identifying and responding to climate change impacts to cultural landscapes: six case studies in eastern U.S. park units. This draft tool is intended to provide basis to assess vulnerability of all 167 cultural landscapes.
Anderson 2016/Alaska National Historic Landmarks	Assess climate change threats to six National Historic Landmarks in Alaska, emphasizing archeological resources, and develop methods for assessing site condition and climate change vulnerability that can be used in evaluating other Alaskan National Historic Landmarks.

Table 4-3 (continued). Abbreviated management objectives and goals of NPS CRVA reports.

Report(s)/Focus	Study Objectives & Goals
Stein-Espanola, in draft/Pacific Islands	Assess climate change vulnerability for Pacific Islands National Historic Landmarks including potential adaptation measures and developed a ranked priority listing for actions. Also to offer guidance for applying this process to non-National Historic Landmark cultural resources.
Melnick et al 2016a; PWR Cultural Landscapes; Melnick et al 2016b	Use the method from Melnick et al. 2015 to evaluate climate change threats to six PWR cultural landscapes. A decision-making matrix and desktop protocol are associated with this report.
Melnick et al. 2017, PWR Cultural Landscapes	In Phase II of the 2016 effort, focus on exposure and sensitivity of contributing characteristics of cultural landscape to climate change.
Fatorić and Seekamp 2016; 2017/CALO	Prioritize historic structures (using data from workshop and report) at CALO Structured Decision Making is the featured method, intended as an example for other historic structures.
Allen 2017/CAHA	Assess historic structures exposure to climate change impacts at CAHA, and document data processing and analytical protocols to facilitate replication of this method.
Ricci et al. 2019a/COLO	Conduct integrated assessment of archeological resources, historic structures, and some natural resources at COLO. Employ POSE (physical, organizational, social, and economic) method and provide a template for other coastal units.

<u>Amberg et al. 2012, Badlands National Park</u>
The VA for BADL had two major goals: first, to assess the potential vulnerability to climate change of natural and cultural resources; and second, to provide a pilot study location for developing a methodology for projecting regional climate changes and a process for assessing resource vulnerability. Objectives to accomplish those goals included:

- Identify species, plant communities, and other resources likely to be most affected by projected climate shifts, and associated physical and ecological changes;
- Describe why these resources are likely to be vulnerable, including the interaction between climate variation and existing stressors to resources; and
- Develop guidance for conducting VAs that engage resource managers and key stakeholders.

<u>Newland 2013, Point Reyes National Seashore</u>
The management goal for this report was to assess the climate change vulnerability of 88 indigenous archeological sites. Objectives to accomplish this included compiling evidence for climate change threats to the sites, describing the threats that climate change poses to those resources, ranking them in order of highest to lowest vulnerability, and proposing options for minimizing and mitigating impacts.

<u>Wilson 2014, NPS Museum Facilities</u>
The museum facilities climate change report management goal was to meet the requirements of Item 1.D. of NPS Policy Memorandum 14-02: Evaluation of Siting of Museum Facilities and Collections

by suggesting a VA for NPS museum facilities across all regions of the NPS. Objectives to accomplish this goal included assessing risk types and recommending priorities for short-term and long-term mitigation actions.

Nersesian and Ehler 2015; National Park Service 2014b; c

The goal of this presentation was to offer a method for scoring vulnerability of resources at GATE, with emphasis on Superstorm Sandy, and prioritize limited funding, staffing, and equipment for protective actions. Objectives included ranking 330 contributing structures using National Register criteria, use potential, and unique significance to the park.

Peek et al. 2015, Continental U.S. coastal parks

The management goal for this project was to determine the exposure of assets in 40 NPS coastal park units to climate change impacts. To accomplish this, objectives included projecting sea-level rise (SLR) threat for one meter exposure of the NPS coastal units, and to identify resources and infrastructure at risk using existing databases such as NPS Facilities Management Software Systems (FMSS).

Anderson 2016, Alaska National Historic Landmarks

The goal of this collaborative project was to evaluate climate change and other threats to six Alaskan National Historic Landmark (NHL) archeological sites, and raise national awareness of the significance of northern NHL sites and their vulnerability to climate change impacts. Objectives included outreach and collaboration with local communities and NHL landowners, developing and implementing a project research design, creating site condition and climate change VA methods and field forms, visiting a sample of NHLs, and a final technical report of project findings and recommendations.

Stein-Espanola, in draft, Pacific Island National Historic Landmarks

This report's management goal was to characterize potential climate change impacts to Pacific Island NHLs, and recommend potential adaptation measures. Objectives to accomplish this goal included creation of three prioritization lists ranking the NHLs most susceptible to climate change impacts through integrated VAs, characterizing adaptive capacities, and a model assessment methodology for other significant cultural resources.

Melnick et al 2015, Eastern U.S. cultural landscapes

The management goal of this report was to assist NPS superintendents, resource managers, partners, communities, and other on-site decision-makers to make informed decisions about identifying, evaluating, and responding to the effects of climate change phenomena on cultural landscapes. Objectives included assessment of six cultural landscapes from mountain and coastal parks of the eastern U.S., and development of management strategies, options, and actions to help NPS personnel understand the ways that climate change is altering individual cultural landscapes.

Melnick et al. 2016a; b: Pacific West Region cultural landscapes

The goal of this project was to respond to the growing need to understand the potential effects of projected climate trends and events on cultural landscapes. Management objectives included building on the Melnick et al. 2015 effort by offering a range of potential actions or "decision trees" based on results of the previous work and applying this method to six PWR cultural landscapes.

Melnick et al. 2017, Pacific West Region cultural landscapes
The goal of this project was to continue the 2016 effort with a preliminary VA for contributing characteristics and features of three PWR cultural landscapes (with special focus on impacts to physical condition and integrity). Objectives to accomplish this goal included assessment of historical exposure, projected exposure, and sensitivity of each cultural landscape-defining characteristic and feature, relative to historical and projected exposures. This phase did not include final vulnerability scoring of the characteristics and features, but the goal was to provide a basis for doing so in the future.

Fatorić and Seekamp 2016; 2017, Cape Lookout National Seashore
The management goal of both projects was to develop a measurement framework for evaluating and assessing the relative historical significance and use potential of historic buildings. Objectives included workshops and meetings, assessing the utility of the Structured Decision Making (SDM) process for cultural resources specifically, and establishing decision rules for how specific adaptation actions would impact historical significance.

Allen 2017, Cape Hatteras National Seashore
The management goal of this project was to assess the vulnerability of historic structures to climate-change related inundation and shifting shorelines. To accomplish this, objectives included development of a multi-hazard framework approach to SLR threats (e.g., including shoreline change, inundation, and storm surges); using multiple spatial contexts through inclusion of planning horizons, surrounding jurisdictions, and the potential for tipping points in physical vulnerability; and documentation of data processing and analytical protocols to promote transferability at other sites.

Ricci et al. 2019a, Colonial National Historical Park
The management goal of this study was to pilot a method for integrated resources VAs at COLO. Objectives to accomplish this included integration of existing data, local knowledge and subject matter expertise; use of the POSE method (physical, organizational, social and economic); incorporation of workshop feedback to produce transferable results for other coastal park units; and detailed analysis of this approach for future use in adaptation planning and interpretation for COLO and other park units.

Key Vulnerability Terms
The use of a combination of exposure and sensitivity to assess vulnerability is clearly set out in the NPS Cultural Resources Climate Change Strategy (Rockman et al. 2016). To date, the NPS reports suggest that the state of current VA practices is at a stage where extant climate data allow for reasonable projections of exposure, but the sensitivity of cultural resources has been unevenly described and explained. In some cases, the reports proceed directly from exposure to vulnerability, setting up a binary result: a resource either is, or is not, vulnerable. This leaves out the relationship between a resource's intrinsic properties and its vulnerability to extrinsic impacts, reduces understanding of adaptive capacity and limits the ability to scope adaptation options. Measuring

sensitivity of cultural resources requires specialized knowledge of characteristics and properties, the significance of those characteristics, and how those characteristics are likely to interact with climate phenomena. Thus, cultural resources subject matter expertise is, and will continue to be, essential to successful description and measurement of sensitivity, and overall assessment of vulnerability. The NPS CRVA report definitions and uses of these terms are summarized below, and definitions will be synthesized in the Results section of this report.

Exposure

The Intergovernmental Panel on Climate Change defines exposure as "the presence of … cultural assets in places and settings that could be adversely affected" (Field et al. 2014; IPCC 2014). Of the 14 NPS CRVA reports studied, five define the term "exposure"; six use the term but don't define it; and three do not use the term (Table 4-4). Several of the CRVA reports mention the extrinsic character of exposure relative to cultural resources (Ricci et al. 2019a; Stein-Espanola, in draft), and use of exposure as a measure of the magnitude of change experienced from stressors (Amberg et al. 2012; Melnick et al. 2016b; Ricci et al. 2019b).

Table 4-4. Summarized exposure definitions from NPS CRVA reports.

Report(s)/Focus	Exposure Definition
Amberg et al. 2012/BADL	'Exposure is a measure of the amount of climatic and environmental change that a species or system is likely to experience' (p. 3).
Newland 2013/PORE	Threat assessment is used. Threats listed, with present/absent.
Wilson 2014/Museums	Exposure is assessed on a facility basis, as present/absent.
Nersesian and Ehler 2015; NPS 2014b; c/GATE	Term is not used. Storms and SLR named.
Peek et al. 2015/Coastal	Exposure is used but not defined. "Risk" used in similar manner.
Anderson 2016/Alaska NHLs	Term is used but not defined. Attributes are listed. "Specifically, archaeological site risk for negative climate change impacts is seen as a combination of both hazard and vulnerability. Hazards are physical processes or events, while vulnerability is the degree of site exposure to hazards. While this study is focused on site vulnerability, hazards must be considered in determining site vulnerability" (p. 2).
Stein-Espanola, in draft/Pacific Isl.	Exposures are defined as extrinsic factors such as climate, temperature, precipitation, drought and hydrology, etc. (p. 7 of draft document).
Melnick et al. 2015/E. Cultural Landscapes	Exposure is "presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected (IPCC 2014)" (p. 18).
Melnick et al 2016a; PWR Cultural Landscapes; Melnick et al 2016b	Term is used but not defined. "... archaeological site risk for negative climate change impacts is ... a combination of both hazard and vulnerability. Hazards are physical processes or events, while vulnerability is the degree of site exposure to hazards" (p. 2).

Table 4-4 (continued). Summarized exposure definitions from NPS CRVA reports.

Report(s)/Focus	Exposure Definition
Melnick et al. 2017, PNW Cultural Landscapes	Exposure = Likelihood x Intensity x Confidence. Historical exposure is "historical rates and ranges of past climate events and trends in cultural landscape locations." Projected exposure is "the best available climate science projections of anticipated changes in temperature, precipitation, SLR, and other projected secondary variables, such as storm event frequency, drought, and wildfires" (p. 17).
Fatorić and Seekamp 2016; 2017/CALO	Exposure is the sum of each climate change impact type (p. 12).
Allen 2017/CAHA	Term not used. Hazards described and assessed on metric basis according to spatial location. If historic district intersects with a modelled projection, it's inferred as exposed.
Ricci et al. 2019b	Exposure defined as "magnitude of change in climate and other stressors that a resource, asset, or process has already or may experience in the future" (Glossary p. 57).

Exposure Case Studies: Gateway National Recreation Area and Badlands National Park

When vulnerability is assessed in response to a major event, terminology and procedures may be targeted and reactive to that specific event. In the case of Superstorm Sandy's effects on the Sandy Hook area of GATE, assessments did not make reference to exposure (National Park Service 2014b; c; Nersesian and Ehler 2015). Rather, they described specific threat types (e.g., erosion, saltwater incursion, and SLR) indicative of the obvious and immediate effects of Superstorm Sandy.

By contrast, the Amberg et al. 2012 report for BADL, which works from a mostly natural resources/ecosystem framework, closely defines exposure as "a measure of the amount of climatic and environmental change that a species or system is likely to experience" (p. 3). This definition is relatively simple to operationalize for cultural heritage resources. Exposure in the BADL case is measured as the degree of departure from historic climate parameters, in this case represented by mean annual minimum and maximum temperatures and total precipitation. Additionally, specific threats and stressors (e.g., fire, increased invasives) were included for species and plant communities. Regarding cultural resources (listed as archeological resources, museum collections including archives and field documentation, historic and prehistoric structures, ethnographic resources, and cultural landscapes), stressors are listed as temperature, precipitation, humidity, fire, wind, and biological infestation. Overall, the NPS CRVA reports are relatively consistent in attention to exposure and how it is assessed. Where the term "exposure" is absent, risk, threat, and hazard are used in the same way.

Sensitivity

Once exposed to a stressor, a resource's potential to be harmed largely depends on its inherent properties. Assessing sensitivity, defined as a measure of susceptibility to harm, is a necessary step in VAs that allows us to understand how big the change could be, and whether it can be moderated or reduced. Table 4-5 below summarizes sensitivity definitions from the NPS CRVA reports.

Of the 14 CRVA reports, eight do not refer to sensitivity; one uses but does not define it; and four reports define sensitivity. In studies where sensitivity is not explicitly defined, researchers generally proceed directly to vulnerability analysis (e.g., Fatorić and Seekamp 2017; Melnick et al. 2015; 2016a; Peek et al. 2015). This is consistent with the spatial or map-based approach to exposure, which judges if a resource is, or is not, in the path of an impact. Although this may be effective where exposure is basically equivalent to total loss (e.g., storm surge impacts to delicate archeological remains), the variable capacity for exposure to change cultural resources should be expressed in scalar terms.

Table 4-5. Summarized sensitivity definitions from NPS CRVA reports.

Report(s)/Focus	Sensitivity Definition
Amberg et al. 2012/BADL	Sensitivity is a measure of the degree to which a system is affected, either adversely or beneficially, by a given change in climate (p. 3).
Newland 2013/PORE	Term is used but not defined. Sensitivity is used in association with probability of cultural resources being present at a given location.
Wilson 2014/Museums	Term is not used.
Nersesian and Ehler 2015; NPS 2014b; c/GATE	Term is not used.
Peek et al. 2015/Coastal	Term is not used
Anderson 2016/Alaska NHLs	Term is not used
Stein-Espanola, in draft/Pacific Isl.	"...sensitivities are intrinsic factors such as the phenology and environmental cues, interactions and community structure." on p 7 of draft document.
Melnick et al 2015/E. Cultural Landscapes	Term is not used.
Melnick et al 2016a; PNW Cultural Landscapes; Melnick et al 2016b	Term is not used.
Melnick et al. 2017, PNW Cultural Landscapes	"...a measure of a cultural landscape's susceptibility to negative impacts which includes damage, deterioration, and/or loss of integrity, resulting from exposure to climate variables." Sensitivity is a measure of whether and/or how a characteristic or feature is likely to be negatively impacted by a specific climate variable. (p. 18).
Fatorić and Seekamp 2016; 2017/CALO	Term is not used.
Allen 2017/CAHA	Term not used. Susceptibility is used in a similar manner.
Ricci et al. 2019b	"(The) degree to which a resource, asset, or process is or could be affected, either adversely or beneficially, by climate variability or change" (p. 57).

Sensitivity can be addressed either proactively or reactively. Proactive sensitivity evaluates the potential of a resource to be harmed by a stressor, based on active measures undertaken by human stewards. Reactive sensitivity is defined as inherent properties that affect the potential to be harmed by a stressor. In NPS CRVA reports that address sensitivity, proactive approaches include seawalls, stabilizing vegetation, fire fuel reduction, and other actions to protect or mitigate for climate change impacts. Reactive approaches assess resiliency to climate change impacts; for example, soil composition, elevation above sea level, and existing management capacities such as staffing. Both have a role in assessing vulnerability and are important steps for scoping adaptation options.

Sensitivity Case Study: Pacific West Region Cultural Landscapes

The PWR CRVA project illustrates the complexity of formulating exposure and sensitivity measures. Melnick et al. (2016a) worked with a multidisciplinary team of experts from the NPS and University of Oregon to draft a protocol and VA framework for six cultural landscapes in the Pacific West Region. During evaluation of the draft report, NPS reviewers noted that the matrix consisted of raw data that included identification of the following:

1. Contributing features of the cultural landscape (provided by NPS)
2. Climate projections, including intensity and confidence, but not of likelihood (prepared by Melnick using the protocol outlined in Appendix C of the Phase I report)
3. Current and historical site impacts (provided by NPS)
4. Current hazards (Melnick prepared a low-resolution assessment of national GIS hazard maps using the protocol outlined in Appendix B of the Phase I report)

This approach provided a measure of exposure, but not of cultural resource sensitivity. Due to ongoing revision of the vulnerability equation itself during that time, the final version of the vulnerability matrix was deferred to a second phase. Melnick et al. (2017) gathered historical climate data and further developed the VA framework in three cultural landscape case studies. The authors added the component of departure from historic conditions and projected exposure using the equation: (historical exposure + projected exposure) x sensitivity = vulnerability. In this report, sensitivity is defined as "a measure of a cultural landscape's susceptibility to negative impacts which includes damage, deterioration, and/or loss of integrity, resulting from exposure to climate variables." This has proven difficult to quantify, and the use of sensitivity within the framework of climate change adaptation for cultural landscapes remains under revision.

Vulnerability

The NPS Cultural Resources Climate Change Strategy's definition of resource vulnerability with respect to climate change is vulnerability = exposure + sensitivity (Rockman et al. 2016). Most of the NPS CRVA reports define and calculate vulnerability by combining exposure and sensitivity, and the scale (extent) of assessment and types of resources (as well as the level of support and area of researcher expertise) influence the choice to use qualitative/descriptive data, quantified/scalar data, or both. Vulnerability definitions and methodologies for analysis were varied in the reports as shown in Table 4-6.

Table 4-6. NPS CRVA reports vulnerability definitions and methodologies.

Report(s)/Focus	Vulnerability Definition	Methodology
Amberg et al. 2012/BADL	"...the extent to which a species, habitat, or ecosystem is susceptible to harm from climate change impacts" (Schneider et al. 2007, as cited by Stein and Glick 2011). Three key components: 1) sensitivity of a system to climate changes; 2) exposure of a system to climate changes; and 3) capacity to adapt to those changes (IPCC 2007).	Qualitative
Newland 2013/PORE	Term is used but not defined. High/Medium/Low derived from summed threats.	Quantitative and Qualitative
Wilson 2014/Museums	Term is not used. Vulnerability of facility is present/absent based on whether risk is present/absent.	Quantitative and Qualitative
Nersesian and Ehler 2015; NPS 2014 b; c/GATE	Term used but not defined (no impact, minimal, moderate, extensive rating based on damage from Hurricane Sandy).	Quantitative and Qualitative
Peek et al. 2015/Coastal	Term is used but not defined. Vulnerability is present/absent based on whether risk is present/absent.	Quantitative
Anderson 2016/Alaska	"Vulnerability is defined as the potential that climate change–induced hazards will have an adverse impact on archaeological sites." Vulnerability is the degree of site exposure to hazards" (Appendix A).	Quantitative and Qualitative
Stein-Espanola, in draft/Pacific Isl.	Exposure + Sensitivity = Potential Impact, and Potential Impact – Adaptive Capacity = Vulnerability.	Quantitative and Qualitative
Melnick et al 2015/E. Cultural Landscapes	Term is used but not defined. Identifies character-defining resources that are most likely to be seriously impacted by climate change.	Quantitative and Qualitative
Melnick et al 2016a; b; PNW Cultural Landscapes	Vulnerability = (Historical exposure x sensitivity) + (Projected exposure x sensitivity).	Quantitative and Qualitative
Melnick et al. 2017; PNW Cultural Landscapes	Vulnerability = (Historical exposure x sensitivity) + (Projected exposure x sensitivity).	Quantitative and Qualitative
Fatorić and Seekamp 2016; 2017/CALO	Vulnerability = Exposure + Sensitivity (2016).	Quantitative and Qualitative

Table 4-6 (continued). NPS CRVA reports vulnerability definitions and methodologies.

Report(s)/Focus	Vulnerability Definition	Methodology
Allen 2017/CAHA	Term is used but not defined. Vulnerability of resource is present/absent based on physical exposure to threat.	Quantitative
Ricci et al. 2019b	"The degree to which a resource, asset or process is susceptible to adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed; its sensitivity; and its adaptive capacity."	Quantitative and Qualitative

Five of the CRVA reports use but do not define the term vulnerability and one (the Museum facilities study) does not use the term although the concept is present. Of the seven reports that do define vulnerability, three describe it as a direct function of exposure (e.g., the resource is in the path of an impact or it is not). This approach conflates vulnerability with exposure. Stein-Espanola (in draft) and includes adaptive capacity in their definition of vulnerability, subtracting it from exposure and sensitivity.

Cultural Resources and Adaptive Capacity

The vulnerability of a resource is integral to, but separate from, adaptation options. In natural systems, living organisms can adapt behaviorally and/or differentially transmit favored or disfavored forms across generations. By contrast, cultural resources—at least, tangible resources—are in a continual state of departure from the conditions in which they were created. They cannot "reproduce, migrate, or self-repair" (Amberg et al. 2012) in response to stressors. Thus, the NPS Cultural Resources Climate Change Strategy (Rockman et al. 2016) states that "cultural resources are, or often include, components that are non-living and as such they have limited capacity to adapt to changing conditions." For example, contributing elements of cultural landscape may include live plant species and communities; in contrast, archeological resources are non-living. Therefore "...a focus for climate change adaptation is *our management of them*" (Ibid p. 3, emphasis added). The adaptive capacity of stewardship and management are outside the scope of this study, and worthy of further exploration. Figure 4.3 illustrates the vulnerability equation for cultural resources adaptation (Ricci et al. 2019b).

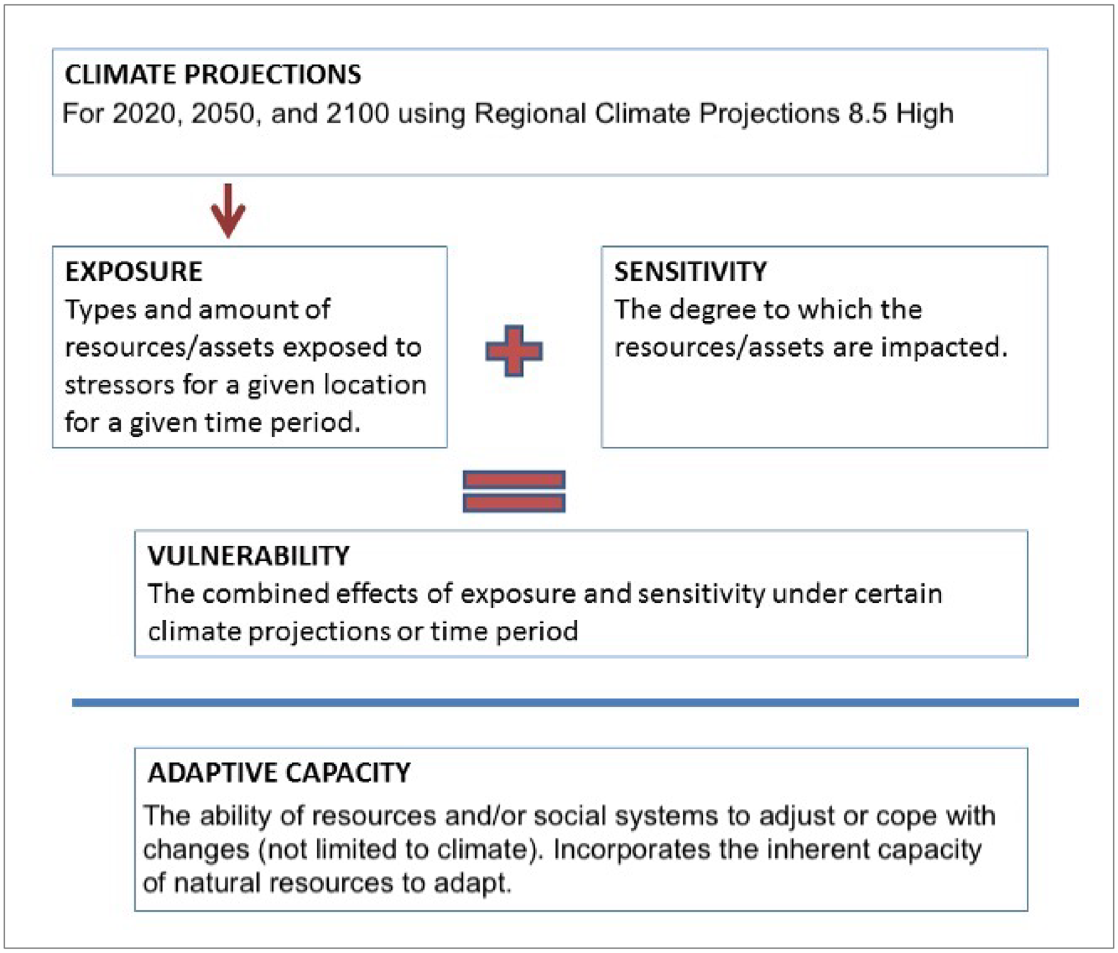

Figure 4-3. Vulnerability equation illustrating separate nature of cultural resources adaptive capacity (Ricci et al. 2019b).

Combining Methodologies

Of the CRVAs studied for this project, most use a combination of qualitative and quantitative methodologies to assess vulnerability. One report uses qualitative means only, and two use quantitative means only. It is notable that quantitative-only approaches are characteristic of large scale (extent) assessments that measure impacts from "the climate-down" using a spatially based approach of overlay or intersection methods to determine exposure of individual resources (e.g., Allen 2017; Peek et al. 2015). As mentioned above, this type of analysis can be accomplished with extant data in a desktop approach and may be suitable for total loss scenarios. However, data pertaining to sensitivity are generally missed in this approach.

At the other end of the spectrum, qualitative-only characterizations capture fine-grained information on the variety, diversity, and unique characteristics of stressors, exposure, and sensitivity of cultural resources. Qualitative methods are more characteristic of a "resources-up" analysis (e.g., Nersesian and Ehler 2015; Newland 2013) and informed by site specific knowledge. However, this kind of data requires specific expertise, field visits, and ideally consultation with interested parties. Also, the unique and distinguishing attributes that are highlighted by this approach can make measurement and comparison difficult at larger scales (extents).

Anderson (2016) has a different take on the two approaches, describing them as "model-based" versus "site-specific." The modelling approach carries costs and benefits:

"The strength of … models is in their ability to combine large amounts of existing data in a spatial format that works well for planning purposes. At the same time, predictive models are hampered by the availability and resolution of data—both cultural and environmental—that can be input into the model. In addition, modeling of larger geographic areas tends to yield coarser outputs."

As VAs are intended to facilitate comparisons that lead to prioritization for critical areas for action, coarse-grained output risks missing important data for decision making. For example, if a resource does not lie within the modelled path of a stressor, and the model/projection expectations do not conform with subsequent events, an assignment of low priority and therefore deferred action could lead to damage or loss from threats that were unanticipated. This is of particular importance if prioritization has been done without input from affected local communities or consulting partners.

For this reason, Anderson (2016) notes that a site-specific approach is essential for addressing the gaps of predictive modeling and obtaining higher precision data on site condition and vulnerability that are needed for long-term resource management planning purposes (Table 4-7). This can be achieved both by modeling at multiple scales, and by combining model predictions with the result of regional field studies.

Table 4-7. Strengths and challenges of modelled versus site specific assessments. Adapted from Anderson, 2016.

Method	Strengths	Challenges
Predictive modeling	• Can use existing data • Spatial format • Multidisciplinary	• Data availability and resolution • Too coarse at large scales • Requires complex multidisciplinary data/teams
Site level assessments	• Current information on site status • Fine-grained data • Can use new data to refine predictive model	• Consistency in data collection • Hard to decide factors/weighting • Only accounts for archeological significance of sites

Combined Methodologies as a Prioritization Tool

Anderson (2016) presents a balanced case for combining modeled approaches with detailed site-level assessments of vulnerability, risk, and current conditions. In order to maximize benefits from both, Anderson scoped modeled data, conducted site level assessments, and combined data into bands that facilitate ranking for prioritization (Table 4-8).

Table 4-8. An example using an index to prioritize sites for treatment, as adapted from Anderson, 2016. In this case, the site prioritization score is 33, obtained by multiplying the total site risk score (11) with the site significance score (3).

Category	Factor	Score
Site risk	Hazard	3 [A]
	Site vulnerability	3 [A]
	Aggregated hazard time frame	3 [B]
	Site condition	2 [C]
	Site risk total	11
Site significance	Site significance	3 [D]

[A] Hazard/vulnerability scale: 1: low, 2: moderate, 3: high

[B] Time frame scale: 1: long term, 2: moderate term, 3: imminent (or unknown)

[C] Condition scale: 1: poor/destroyed, 2: fair, 3: good

[D] Significance scale: 1: low, 2: moderate, 3: high (or unknown)

Nersesian and Ehler (2015) also used a banding method for historic structure management actions in response to the impacts of Superstorm Sandy. Raw data were pooled into Not Impacted, Minimal Vulnerability, Moderate Vulnerability, and Extensive Vulnerability. Ricci et al.'s (2019a; b) integrated approach to data uses a detailed process to derive exposure quantitatively with composite scores for each type of impact to a resource. To assess sensitivity, researchers combined quantitative exposure composite scores with qualitative sensitivity indicators. Sensitivity could then be scored as high/medium/low. This allows qualitative information to be grouped into clusters, "binned" into ordinal categories, and then used for measurement, comparison, and prioritization for action. Ricci and co-authors go so far as to combine raw vulnerability scores into further "bins" using obvious break points in the data.

Each approach to data type and structure has strengths and weaknesses. The combined or "banding" approach has the advantage of both allowing fine grained information to inform large scale data, and a comparative approach to be applied to individual resources with unique characteristics. This type of analysis will improve the validity of analytic results with repeated cycles over time. Table 4-9 summarizes these characteristics with three examples from the CRVA reports.

To summarize, modeled and/or quantitative approaches can be useful for rapid large-scale (extent) assessments that determine whether a resource will be exposed to a stressor. This works best for one big phenomenon, such as SLR. Empirical and qualitative approaches are useful for capturing fine-grained information that contribute to the analysis of sensitivity. This is most useful in gauging an individual resource's amount of departure from historic baseline conditions. A combined approach that uses banding or binning to create category clusters is a flexible and powerful technique for rendering detailed data into measurable and comparable groupings for the assessment of vulnerability, and subsequent prioritization.

Recommendations and Best Practices from the Cultural Resources Vulnerability Assessments

In the CRVA reports, recommendations served two primary purposes: 1) furthering the protection of the resources under assessment, and 2) serving as an example for future VAs. Recommendations from the reports are summarized in Table 4-10.

Several of the CRVA reports offer specific recommendations. Where there is no recommendation presented, the methods themselves are an example and a recommendation for future use. Apart from the museum facility report (Wilson 2014), the CRVA reports demonstrated their methods with the implication of transferability, or clearly stated that their methods are intended to be transferable. Examples include Fatorić and Seekamp (2016; 2017), who demonstrate the application of resource use potential alongside significance where appropriate, consider long time horizons, and include treatment costs in adaptation planning. Anderson (2016) makes the case for a two-phase approach of assessing exposure and sensitivity, beginning with remote/modelled data and confirming with site-based data. Ricci et al. (2017; 2019a; b) offer a review of past studies, and guidance for conducting climate change VAs in coastal national parks with a focus on Northeast Region parks natural resources. Their recommendations apply broadly and are summarized below.

1. Conduct Integrated VAs wherever possible (e.g., include multiple resource categories).
2. Assemble collaborative teams and sub-teams, use break-out groups for specific resource expertise.
3. Maintain progress through flexible teamwork opportunities (in-person workshops and remote meetings).
4. Use the exposure + sensitivity = vulnerability equation.
5. Keep adaptive capacity separate from, and following on, exposure and sensitivity analyses. Adaptive capacity for cultural resources is made up of human actions extrinsic to cultural resources.
6. Start with a remote quantitative approach that uses projections/models, then incorporate fine-grained local data.
7. Use the "binning" method to cluster data according to natural breaks. This can be done at the level of exposure, sensitivity, vulnerability, and adaptive capacity.
8. Build and maintain community partnerships that emphasize local participation.

Table 4-9. Comparison of quantitative and qualitative methodologies using three CRVA case studies.

Study	Proximity	Emphasis	Relatedness	Data type	Rank-ability	Exposure vs. Sensitivity
Quantitative/Modeled Method (e.g., Peek et al. 2015)	Desktop/large scale	Climate-Down	Intersectional/ layered	Quantitative Mostly	High	Exposure
Qualitative/Empirical Method (e.g., Amberg et al. 2012)	Site-Based/fine scale	Resource-up	Point/Polygon	Qualitative Mostly	Low	Both included
Banded/Combined Method (e.g., Ricci et al. 2019b)	Begin with large scale, ground-truth at fine scale, repeat	Downscaled model data and site data	Relational	Both	High	Both included

Table 4-10. NPS CRVA report recommendations.

Report(s)/Focus	Study Objectives	Report Recommendations
Amberg et al. 2012/BADL	Conduct an integrated natural and cultural resources assessment for BADL; provide template and guidelines for other NPS units. Includes ethnography and brief section on archeology.	No specific recommendations. The intent was to assess vulnerability only.
Newland 2013/PORE	Compile evidence for climate change threats to 88 indigenous archeological sites at PORE, describe the threats, rank sites in order of threat level, propose options for minimizing and mitigating for impacts.	Detailed recommendations include inventory of archeological sites, data recovery and treatment actions, and continued engagement with associated indigenous communities.
Wilson 2014/Museums	Gather data on climate change natural hazard risks to museum facilities for all regions of the NPS.	No specific recommendations. Adequate staffing is called out as critical to adaptive capacity for museum facilities.
Nersesian and Ehler 2015; NPS 2014 b; c/GATE	Develop a process for prioritizing historic structures at GATE for protective and mitigation actions, as part of a larger resource management plan.	No specific recommendations. Scoring method allows for “preserve, stabilize, and ruin” banding using vulnerability scores.

Table 4-10 (continued). NPS CRVA report recommendations.

Report(s)/Focus	Study Objectives	Report Recommendations
Peek et al. 2015/Coastal	Predict exposure of cultural and historic facilities including buildings, to one meter of SLR across 40 coastal parks.	Recommends clustering data into two simple exposure categories: high and limited. Also recommend that NPS begin regional and nationwide climate change adaptation plans.
Melnick et al 2015/E. Cultural Landscapes	Develop a method for identifying and responding to climate change impacts to cultural landscapes: six case studies in eastern U.S. park units. This draft tool is intended to provide a basis to assess vulnerability of all 167 cultural landscapes.	Recommends a scenario planning method for assessing vulnerability to climate change. Identifies adaptation options (e.g., manage change, improve resiliency, document and release). Individual cultural landscapes receive adaptation option recommendations.
Anderson 2016/Alaska NHLs	Assess climate change threats to six NHLs in Alaska, emphasizing archeological resources, and develop methods for assessing site condition and climate change vulnerability that can be used in evaluating other Alaskan NHLs.	Robust recommendations for management of specific NHLs include community-related actions, education/outreach with stakeholders, and future monitoring and mitigation.
Stein-Espanola, in draft/Pacific Isl.	Assess climate change vulnerability for Pacific Islands NHLs including potential adaptation measures, and develop a ranked priority listing for actions. Also, to offer guidance for applying this process to non-NHL cultural resources.	Recommendations include assigning numeric impact value to exposure types for each resource and assessing adaptive capacity separate from vulnerability. Also, specific mitigation options for adaptation are recommended for individual NHLs.
Melnick et al 2016a; PWR Cultural Landscapes; Melnick et al 2016b	Use the method from Melnick et al. 2015 to evaluate climate change threats to six PWR cultural landscapes. A decision-making matrix and desktop protocol are associated with this report.	Recommend collecting small-scale data for particulars of cultural landscapes and local climate and environment; increasing consistency with regard to timing/seasonality of studies and assessment tools used; and linkage with FMSS.
Melnick et al. 2017, PWR Cultural Landscapes	In Phase II of the 2016 effort, focus on exposure and sensitivity of contributing characteristics of cultural landscapes to climate change.	Recommendations are primarily for Phase III (in process; will deal with adaptation). They include quantification of climate change impacts on significance and contributing features of cultural resources, continued input from local staff and other experts, use of both large scale and local/qualitative data.
Fatorić and Seekamp 2016; 2017/CALO	Prioritize historic structures (using data from workshop and report) at CALO. Structured Decision Making (SDM) is the featured method, intended as example for other historic structures.	Recommend SDM as primary method as means to develop implementable alternative adaptation actions. Can be grouped into resource- or unit-specific portfolios and cross-cutting portfolios.

Table 4-10 (continued). NPS CRVA report recommendations.

Report(s)/Focus	Study Objectives	Report Recommendations
Allen 2017/CAHA	Assess historic structures exposure to climate change impacts at CAHA, and document data processing and analytical protocols to facilitate replication of this method.	Recommendations include maximizing extant data; ongoing monitoring and updating of sea level data with other agencies.
Ricci et al. 2019a/COLO	Carry out integrated method for assessing archeological resources, historic structures, and some natural resources COLO to climate change. Intent is to provide template for other coastal units.	Report recommends use of collaborative workshop methodology, featuring the POSE method for assessing exposure. Methods explicitly call for integrated analysis.

4.7 Discussion: Outcomes, Gaps, and Opportunities

The outcomes of the CRVA reports reflect the varied approaches taken in reaching the common goal of assessing vulnerability of cultural resources. Table 4-11 below summarizes the CRVA outcomes in attaining their stated objectives. Successful means that the report accomplished its objectives, largely successful describes a report that substantively met its objectives with only minor omissions, and partly successful means that some objectives are un-met. This last category is not necessarily a shortcoming, as some of the reports are in multiple phases and not yet complete.

Several gaps, and corresponding opportunities, stand out in this summary analysis. They are listed below by theme.

Table 4-11. Outcomes of NPS CRVA reports.

Report(s)/ Focus	Success Level	Missed Opportunities	Accomplishments
Amberg et al. 2012/BADL	Largely successful	Cultural resources exposure and sensitivity not fully developed and adaptive capacity not within the scope.	First attempt at integrated VA. A convenient guideline for the park that can analyze hazard exposure types across multiple resources.
Newland 2013/PORE	Largely successful	Exposure and sensitivity concepts and methods not used, hard to compare with other efforts.	First attempt at single park-level assessment. Detailed technical discussion useful for hazard analysis of archeological resources.
Wilson 2014/Museums	Largely successful	Exposure and sensitivity terminology and methods not used. Facilities rather than museum objects were units of analysis.	Nationwide risk assessment for museum structures/facilities. Strong descriptors of infrastructure and personnel issues as hazards. Individual region reports very detailed.
Nersesian and Ehler 2015; NPS 2014b; c/GATE	Largely successful	Exposure "after the fact" and limited to storm impacts, sensitivity not addressed. Difficult to compare with other efforts.	Presented at major conference. Use of Superstorm Sandy as a high-profile case study in a major exposure event. Also, use of "banding" method for prioritization.
Peek et al. 2015/Coastal	Largely successful	Addresses exposure only.	Large-scale (extent) analysis of SLR exposure allows for replicability, comparability, and transfer of methodology.
Melnick et al 2015/E. Cultural Landscapes	Partly successful	Exposure and sensitivity terminology and methods not used, not readily compared with, or transferred to other efforts.	Used scenario planning methods to identify adaptation options for 6 cultural landscapes from the eastern U.S.
Anderson 2016/Alaska NHLs	Largely successful	Sensitivity not defined or used (but planned for Phase II).	Six AK NHLs assessed. Useful model-based versus narrative-based methods for analyzing vulnerability data. Advantage: detailed consultation with descendant communities.
Stein-Espanola, in draft/Pacific Isl.	Partly successful	Report draft not yet finalized or distributed.	Exposure, sensitivity, vulnerability, adaptive capacity defined and described relative to climate change. Detailed case studies for individual NHLs are user-ready.

Table 4-11 (continued). Outcomes of NPS CRVA reports.

Report(s)/ Focus	Success Level	Missed Opportunities	Accomplishments
Melnick et al 2016a; PWR Cultural Landscapes; Melnick et al 2016b	Partly successful	Downscaled climate data insufficient resolution to assess exposure for some units. Sensitivity analysis was largely omitted. Difficult to replicate for other units.	This study assessed cultural landscapes in the PWR using six case studies. Solid foundation established through creation of a vulnerability matrix for 160+ cultural landscapes for use in exposure analysis.
Melnick et al. 2017, PWR Cultural Landscapes	Partly successful	Sensitivity analysis to augment 2016 work was the goal of this report but exposure analysis became the focus. The sensitivity analysis is ongoing.	Exposure data complements Melnick et al. 2016 case studies, including the revised exposure matrix.
Fatorić and Seekamp 2016; 2017/CALO	Largely successful	Exposure and sensitivity terms are used but not defined.	Used structured decision making (SDM) process for adaptation planning for 2 historic districts (17 structures). Method is transferrable. Use potential analysis and crosscutting/individual adaptation categories are called out specifically.
Allen 2017/CAHA	Largely successful	This project uses a variety of climate data and models to project sea level rise.	Sensitivity largely omitted from discussion, as individual resources not the focus. Can't assess for high resolution vulnerability. Advantage: Good example of data downscaling; easily transferrable.
Ricci et al. 2019a/COLO	Successful	Highly detailed and technical, a handbook version would be helpful. Sensitivity not explored as fully as exposure.	This study assessed vulnerability of cultural resources for COLO in an integrated manner using workshops and methodologies designed to be transferable. Flexible process allows local and subject matter expertise to contribute to original qualitative/narrative data and allow for greater accuracy in deriving priority bins.

Coherence in audience and authorship.

Gap: Reports were intended for NPS subject matter experts, managers, and leadership. It is not clear how well or in what manner the NPS CRVAs as written support Section 106 consultation (per the National Historic Preservation Act), which is usually needed to take management action.

Opportunity: Scope methods for connecting the climate change VA process with Section 106 procedures in workshops or other team-based exercises.

Variation in analytical breadth: to integrate or not to integrate?

Gap: Integrated VAs that include structures, facilities, and/or natural resources (e.g., plant and animal species, communities, habitats) are strong on exposure but less so regarding sensitivity, adaptation options, and recommendations.

Opportunity: Consider integrated VAs as first-phase assessment that facilitates identification of areas for closer focus. This requires a commitment to subsequent phases or sub-tasks that scope sensitivity, vulnerability, adaptive capacity, and recommended actions specifically for cultural resources.

Use of Team-Based Approaches

Gap: There is no question that this is the preferred method for VAs. However, the right expertise is not always available. Wilson (2014) points out that personnel shortages can weaken the ability to assess vulnerability and therefore capacity for adaptation (for example, NPS curation staff increased by just over 1% between 1998 and 2013, yet the number of items in NPS collections increased 112.4%).

Opportunity: Use Ricci et al.'s (2019b) recommendations to de-centralize and increase flexibility of VAs through expert sub-groups, flexible scheduling, and use of remote and virtual meeting methods. Local expertise is essential to crafting actionable VAs that consider unique local conditions.

Desktop/quantitative vs empirical/site based qualitative methods

Gap: Desktop methods (modelling, remote, second order data) that are quantitative and phenomenon-oriented may sacrifice fine-grained information that is character-defining for cultural resources. In turn, empirical and/or qualitative methods data collection can be inconsistent and hard to compare and rank in priority order, especially in large-scale (extent) analyses.

Opportunity: Teams with diverse expertise allow for both methods. Modeled large-scale (extent) approaches target areas site-based assessment to confirm preliminary findings. High resolution data can then be incorporated to refine and target large-scale (extent) analyses.

Focus on Acute Problems/Geographic Gaps

Gap: Most of the current VAs focus on coastal or island cultural resources. One quarter of NPS units are located in coastal areas with high anticipated impacts from rapid SLR, changes in storm frequency and intensity, and associated coastal land changes (Caffrey et al. 2018). However, climate impacts throughout the NPS system affect all habitats. Further impacts are emerging, combining, and producing unexpected results. Therefore, gaps exist in establishing baselines for long-term change in diverse settings, and in areas where impacts are less obvious than SLR.

Opportunity: Apply what has been learned about vulnerability and adaptation options under rapid onset conditions to slower, emergent phenomena. As with this effort, document the most effective strategies and tactics and make them accessible to a wide NPS audience. Making use of recommendations established in prior studies can increase efficiency and maximize resources for a wide range of problems.

Illustrative Case Studies for NP Adapt and Other Sharing

Table 4-12 summarizes NPS CRVAs for inclusion as case studies in shared contexts.

Table 4-12. NPS CRVA reports as illustrative case studies.

Report(s)/Focus	CR Assessed	Case Study In:
Amberg et al. 2012/BADL	National Park	Integrated natural and cultural resources VA for a single park unit.
Newland 2013/PORE	National Seashore	Climate change threats to archeological sites in a coastal park unit, ranked order of threat level, and proposed protective options.
Wilson 2014/Museums	Museum Facilities	National-scale (extent) assessment of climate change natural hazard risks for museum facilities.
Nersesian and Ehler 2015; NPS 2014b; c/GATE	National Recreation Area	Prioritization process for historic structures as part of a larger resource management plan in a complex coastal park.
Peek et al. 2015/Coastal	Coastal Parks	Large-scale (extent) model of integrated resource exposure to one meter of SLR.
Melnick et al 2015/E. Cultural Landscapes	Cultural Landscapes	Assessment method for cultural landscapes, intended to provide basis to assess vulnerability of cultural landscapes nationwide.
Anderson 2016/Alaska NHLs	NHLs	Threat assessment for arctic NHLs with emphasis on archeological resources and including indigenous perspectives.
Stein-Espanola, in draft/Pacific Isl.	NHLs	Threat assessment for Pacific Islands NHLs climate change vulnerability. Offers a ranked priority listing for mitigation actions.
Melnick et al 2016a; PWR Cultural Landscapes; Melnick et al 2016b	Cultural Landscapes	Evaluation of climate change vulnerability for six PWR cultural landscapes, a decision-making matrix, and a desktop protocol.
Melnick et al. 2017, PWR Cultural Landscapes	Cultural Landscapes	Follow-on assessment of exposure and sensitivity of contributing characteristics of cultural landscapes to climate change.
Fatorić and Seekamp 2016; 2017/CALO	National Seashore	Vulnerability assessment and prioritization of coastal historic structures using SDM (structured decision making) method.

Table 4-12 (continued). NPS CRVA reports as illustrative case studies.

Report(s)/Focus	CR Assessed	Case Study In:
Allen 2017/CAHA	National Seashore	Vulnerability assessment for coastal historic structures using climate model projections and featuring protocols for data processing and analysis.
Ricci et al. 2019a/COLO	National Historical Park	Integrated VA for a coastal park using POSE (physical, organizational, social, and economic) methodology.

Near-Term Recommendations for Future Efforts

Seven actions are recommended to build on the progress made thus far by the 14 NPS CRVAs.

1. The NPS needs to implement data-sharing such as a centralized and secure reports "clearing house" for cultural resources vulnerability researchers. Future research scopes of work should include data sharing as part of deliverables, and this analysis should be updated periodically (e.g., every three to five years) to incorporate VA projects already in planning and or under revision.
2. The definition and usage of key vulnerability concepts and terms for cultural resources can be simplified and made consistent. The following are proposed working definitions.
    a. Exposure is the degree to which a given resource is expected to be affected by a stressor, threat, or hazard.
    b. Sensitivity measures a resource's susceptibility to harm from exposure to a climate-driven stressor, threat, or hazard.
    c. Vulnerability is the sum of exposure and sensitivity.
    d. Adaptive Capacity measures the ability of *human managers and systems* to adjust the use and management of a given resource, and with cultural resources adaptive capacity should be addressed separately.
3. The CRVAs should be considered in an integrated fashion with natural resources and facilities. This is feasible at park, cluster, regional, and national scales (extent). The incorporation of this report with others is an example of this integrated approach.
4. Researchers and NPS managers alike have pointed out a lack of subject matter expertise in integrating natural and cultural resources and facilities, and insufficient project time to dedicate to a focused, collaborative process. The shortage of dedicated time for CRVAs may be partly offset by incorporating external partners, but gaps may remain for park personnel participation. Strategic planning that maximizes support for and results from park personnel efforts and minimizes impacts to their workload should be included in VA scopes of work.
5. Incorporating VA concepts and methods into appropriate cultural heritage educational materials will build on collective progress for the benefit of future cultural heritage

experts. The NPS already has strong partnerships with institutions of higher education and non-profit research organizations in this regard.

6. Ethnographic resources, sometimes termed “intangible heritage,” are also highly impacted by climate change, and deserve vulnerability analysis separately as well as in a supporting role for tangible cultural resources. The NPS's ethnographic overviews and assessments, where available, as well as local community involvement in scoping, should be a part of all CRVAs.
7. Since this study was conducted in 2017-18, several of the near-term recommendations have been scoped or initiated at some National Park units in partnership with research institutions. Updating this study periodically on a five-year basis will offer quantified metrics for accomplishments in recommendations and desired outcomes, and gaps that persist or emerge.

4.8 Conclusion: The State of the Art in Assessing Vulnerability

The variation of reports regarding modelled/quantified versus empirical/qualitative methods for exposure and sensitivity data arose from factors such as the scope of work and researcher areas of expertise (e.g., climate scientist, archeologist, etc.). A combined approach that uses banding of data at breakpoints to create ordinal comparable categories emerged as a flexible and powerful technique for grouping detailed information about diverse categories of resources into measurable, comparable sets or “bands” that can then be organized in priority order.

This study has identified some gaps in coverage (both geographic and resource-based), including a need for clear understanding of exposure and sensitivity in the vulnerability equation, the lack of comparability between integrated and non-integrated methods, the external position of adaptive capacity regarding cultural resources, and a general need for increased access to CRVA products. Overall, the NPS and research partners have made substantial progress including climate change in cultural resources VAs. The accomplishments set forth in the NPS CRVA reports represent the first phases of a methodology that is still under development.

In coming years, the number of CRVAs will grow. The most readily filled gaps will be content-related: e.g., geographic and resource types, with ongoing needs for balance and coordination between methods that reflect local conditions and needs while informing other efforts. In the United States, public land management agencies (e.g., U.S. Forest Service, Bureau of Land Management, and others) are poised to join the NPS in the assessment of cultural resources climate change vulnerability. Further, the NPS is building collaborative networks with the international cultural heritage sector (Rockman et al. 2016), where VAs to tackle similar challenges may offer innovative strategies to adopt or modify. A good example is the strategic use of citizen science monitoring of sensitive sites in Wales, Scotland, Ireland, Brittany, and more (for summary see Rockman et al. 2016), which adds capacity to data collection efforts and builds ownership and participation of cultural heritage stakeholders. In turn, NPS-researcher partnerships and new techniques can help inform international cultural heritage VAs. Translation of reports and methodological guides into other languages will be key to this effort.

In conclusion, this report's findings show growing coherence and forward progress on the CRVAs front through the NPS's strategic facilitation of research within the agency and through partnerships. The Cultural Resources, Partnerships, and Science Program, the Climate Change Response Program, research partners, and stakeholders involved in these efforts are to be commended for forging the "state of the art" for cultural resources imperiled by climate change.

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Appendix A: Evaluated Exposure Assessments

Exposure of NPS Assets to Long-Term SLR (2015)

1. Peek, K. M., R. S. Young, R. L. Beavers, C. H. Hoffman, B. T. Diethorn, and S. Norton. 2015a. Adapting to climate change in coastal national parks: Estimating the exposure of park assets to 1 m of sea-level rise. Natural Resource Report NPS/NRSS/GRD/NRR—2015/961. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2221965

- Protocol/Project: NPS long-term SLR exposure of infrastructure
- Specific Method: Exposure/hazard mapping
- Evaluation Scale(s): Spatial – asset site
- Resource(s): Infrastructure (assets)
- Climate Factors/Hazards: Sea-level rise
- Location: Nationwide, multiple national parks
- Notes: This analysis evaluated the long-term sea-level rise exposure of assets within coastal national parks. Parks were given a designation of high or limited exposure based on available geographic data (digital elevation models, erosion potential, etc.).

2. Peek, K. M., R.S. Young, R.L. Beavers, C.H. Hoffman, B.R. Tormey, B.T. Diethorn, S. Norton, J. McNamee, R.M Scavo, and W.B. Lloyd. In press. Estimating the exposure of national park coastal assets to 1 meter of sea-level rise and associate storms. Natural Resource Report NPS/NRSS/GRD/NRR—in press. National Park Service, Fort Collins, Colorado.

- Protocol: NPS long-term SLR exposure of infrastructure
- Specific Method(s): Exposure/hazard mapping
- Evaluation Scale: Spatial - asset site
- Resource(s): Infrastructure (assets)
- Climate Factors/Hazards: Sea-level rise
- Location: Nationwide, multiple national parks
- Notes: This analysis evaluated the long-term sea-level rise exposure of assets within coastal national parks. Parks were given a designation of high or limited exposure based on available geographic data (digital elevation models, erosion potential, etc.). This completed the remaining coastal parks from the original analysis (Peek et al., 2015).

Individual Studies

3. Murdukhayeva, A., P. August, M. Bradley, C. LaBash, and N. Shaw. 2013. Assessment of inundation risk from sea level rise and storm surge in northeastern coastal national parks. Journal of Coastal Research 29(6a):1–16. http://www.bioone.org/doi/abs/10.2112/JCOASTRES-D-12-00196.1

- Protocol: n/a
- Specific Method: Exposure/hazard mapping + probability

- Evaluation Scale(s): Spatial – asset site
- Resource(s): Sentinel sites – areas of importance, includes infrastructure
- Climate Factors/Hazards: Sea-level rise and storm surge
- Location: Northeast United States, Cape Cod National Seashore (CACO) and Assateague Island National Seashore (ASIS)
- Notes: This study assessed the risk of sea-level rise and storm surge inundation at sentinel sites (areas of importance for natural, cultural, and infrastructure resources) within two northeast region parks (CACO and ASIS). They compared elevation data collected in the field (real-time kinematic GPS) to three modeled datasets: bathtub modeling, Sea Level Affecting Marshes Model (SLAMM), and the Sea, Lake, and Overland Surges from Hurricanes (SLOSH).

4. Monahan, W.B. and N.A. Fisichelli. 2014. Climate exposure of US national parks in a new era of change. PLoS ONE 9 (7), e101302. doi:10.1371/journal.pone.0101302. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0101302

- Protocol/Project: n/a
- Specific Method: Exposure/hazard mapping
- Evaluation Scale(s): Spatial – park
- Resource(s): National parks
- Climate Factors/Hazards: Temperature, precipitation, frost/wet day frequencies, vapor pressure, cloud cover, and seasonality
- Location: Nationwide, multiple national parks
- Notes: This study evaluated the climate change exposure of national parks at the landscape scale. This analysis was meant to help parks understand and interpret their major climate drivers.

5. Rummel, Klepper, and Kahl (RK&K). 2016. Queen Anne's County: sea level rise and coastal vulnerability assessment implementation plan. Prepared for: Queen Anne's County, Department of Public Works, Baltimore, Maryland. http://www.qac.org/DocumentCenter/View/5456/QAC-Sea-Level-Rise-and-Coastal-Vulnerability-Assessment-and-Implementati?bidId

- Protocol: n/a
- Specific Method: Exposure/hazard mapping (referred as vulnerability within study)
- Evaluation Scale(s): Spatial – asset site
- Resource(s): Infrastructure and transportation
- Climate Factors/Hazards: Sea-level rise and storm surge
- Location: Queen Anne's County, Maryland

- Notes: This methodology uses GIS to overlay the modeled scenarios for sea-level rise and flooding with the locations of resources. Example results include the total acreage of land impacted by each scenario, number of impacted emergency service facilities for each scenario, and the miles of evacuation routes impacted by each scenario. This study assessed the coastal vulnerability of Queen Anne's County's infrastructure, private property, and natural resources. Three scenarios were evaluated to assess coastal vulnerability: 1) 2050 projected sea-level rise plus MHHW; 2) 2100 projected sea-level rise plus MHHW; and 3) 2050 project sea-level rise plus MHHW plus storm surge.

Appendix B: Evaluated Scenario Planning Studies

DOT Cape Cod Pilot Project (2011)

6. Place Matters. 2011. Interagency transportation, land use, and climate change pilot project: technical scenario report. Prepared on behalf of U.S. DOT Volpe Center, FHWA, NPS, and FWS, Washington, D.C. https://www.volpe.dot.gov/sites/volpe.dot.gov/files/docs/interagency_tech.pdf

- Protocol: DOT Cape Cod Pilot Project
- Specific Method(s): Exposure/hazard mapping; scenario planning
- Evaluation Scale(s): Spatial - community
- Resource(s): Transportation, land use
- Climate Factors/Hazards: Sea-level rise, erosion, and storms
- Location: Cape Cod, Massachusetts
- Notes: Volpe (DOT) worked with federal, regional, and state stakeholders (FHWA, NPS, FWS, EPA, NOAA, FTA, FEMA, DOD, Cape Cod Commission, CACO, and Cape Cod Regional Transit Authority) to execute a scenario planning pilot project on Cape Cod to integrate climate change into existing and continuing transportation, land use, coastal zone, and hazard mitigation planning processes. No methodology for calculating the vulnerability of specific assets is described. However, data related to climate change factors (elevation, erosion, and exposure to storm surge and sea-level rise) were used as part of the scenario planning process.

7. U.S. Department of Transportation (DOT) Volpe Center. 2011a. Interagency transportation, land use, and climate change pilot project. Prepared with FHWA, NPS, and FWS, Cambridge, Massachusetts.
https://www.volpe.dot.gov/sites/volpe.dot.gov/files/docs/Cape%20Cod%20Pilot%20Project%20One%20Pager_092811.pdf

- Protocol: DOT Cape Cod Pilot Project
- Specific Method: Exposure/hazard mapping; scenario planning
- Evaluation Scale(s): Spatial – region
- Resource(s): Transportation, land use
- Climate Factors/Hazards: Sea-level rise, erosion, and storms
- Location: Cape Cod, Massachusetts
- Notes: Summary document of the Volpe scenario planning pilot project at Cape Cod. The project used a GIS-based software tool called CommunityViz to develop and evaluate a series of transportation and land use scenarios (indicators included vehicle miles traveled, greenhouse gas emission, and percentage of new population in area) in areas vulnerable to climate change impacts, such as sea-level rise, erosion, and storm related events.

8. U.S. Department of Transportation (DOT) Volpe Center. 2011b. Interagency transportation, land use, and climate change Cape Cod pilot project: Cape Cod commission action plan. Prepared with FHWA, NPS, and FWS, Cambridge, Massachusetts. https://www.volpe.dot.gov/sites/volpe.dot.gov/files/docs/ccc_action_plan.pdf

- Protocol: DOT Cape Cod Pilot Project
- Specific Method: Exposure/hazard mapping; scenario planning
- Evaluation Scale(s): Spatial – region
- Resource(s): Transportation, land use
- Climate Factors/Hazards: Sea-level rise, erosion, and storms
- Location: Cape Cod, Massachusetts
- Notes: This document highlights opportunities that the Cape Cod Commission plans to pursue for implementing, improving, and building upon the refined scenario (consolidated scenario from different breakout groups from workshops). These opportunities include the Five-Year Plan for Public Transportation on Cape Cod, the Long-Range Transportation Plan, and the Regional Policy Plan.

9. Rasmussen, B.K., L. Morse, D. Perlman, G. Filosa, and C. Poe. 2012. A framework for considering climate change in transportation and land use scenario planning: Lessons learned from an interagency pilot project on Cape Cod. FHWA-HEP-12-028; NPS 609 /108334. Published by U.S. DOT Volpe Center. Prepared with FHWA, NPS, and FWS, Cambridge, Massachusetts. https://rosap.ntl.bts.gov/view/dot/9349

- Protocol: DOT Cape Cod Pilot Project
- Specific Method: Exposure/hazard mapping; scenario planning
- Evaluation Scale(s): Spatial – region
- Resource(s): Transportation, land use
- Climate Factors/Hazards: Sea-level rise, erosion, and storms
- Location: Cape Cod, Massachusetts
- Notes: This report summarizes the processes followed within the pilot scenario-planning project, as well as lessons learned and recommendations for future projects. Indicators include GHG emissions, development in areas vulnerable to sea-level rise, growth in conservation and resource-constrained areas, and transit accessibility.

DOT Central New Mexico Scenario Planning (2013)

10. U.S. Department of Transportation (DOT) Volpe Center. 2013. Central New Mexico climate change scenario planning project: An interagency transportation, land use, and climate change initiative. Prepared with FHWA, FWS, NPS, BLM, and MRCOG, Cambridge, Massachusetts. https://www.volpe.dot.gov/sites/volpe.dot.gov/files/docs/CentralNM_CCSP_One%20Pager%2011%2025_13.pdf

- Protocol: DOT Central New Mexico Scenario Planning
- Specific Method: Exposure/hazard mapping; scenario planning
- Evaluation Scale(s): Spatial – regional
- Resource(s): Transportation and land use
- Climate Factors/Hazards: Erosion, flooding, temperature/heat, and precipitation/drought
- Location: Central New Mexico
- Notes: One page summary document of the Central New Mexico climate change scenario-planning project. This project, which builds on the 2011 Cape Cod effort, focuses on inland areas, and explores impacts due to water scarcity, heat waves, wildfires, and extreme weather events. Volpe worked with multiple agencies (FWHA, FWS, NPS, and BLM) and the Mid-Region Council of Governments (MRCOG) to influence transportation and land use decision-making in the Albuquerque region by using scenario planning (called the Central New Mexico Climate Change Scenario Planning Project-CCSP). Goals of this project were to: 1) Advance climate analysis in scenario planning, 2) Impact decision-making, 3) Develop a transferrable process, and 4) Build partnerships. No methodology for calculating the vulnerability of specific assets is described. However, data related to climate change factors (flooding, drought, temperature change, wildfires, and extreme weather) were considered in the scenario planning process. Study evaluated how the central New Mexico region could develop in a way that minimizes greenhouse gas (GHG) emissions and increases resiliency to climate change (development footprint, wildfire risk, flood risk, and impacts to crucial wildlife habitat).

11. Ecosystem Management. 2014a. Climate change effects on central New Mexico's land use, transportation system and key natural resources. Task 1.1. Prepared with U.S. DOT Volpe Center and the University of New Mexico, Albuquerque, New Mexico. https://rosap.ntl.bts.gov/view/dot/12198

- Protocol: DOT Central New Mexico Scenario Planning
- Specific Method: Exposure/hazard mapping; scenario planning
- Evaluation Scale(s): Spatial – regional
- Resource(s): Transportation and land use
- Climate Factors/Hazards: Erosion, flooding, temperature/heat, and precipitation/drought
- Location: Central New Mexico
- Notes: This report summarizes potential climate change effects on the availability of water, land use, transportation infrastructure, and key natural resources in central New Mexico (as part of the CCSP in central New Mexico).

12. Ecosystem Management. 2014b. Climate change effects on central New Mexico's land use, transportation system, and key natural resources. Task 1.2. Prepared with U.S. DOT Volpe Center

and the University of New Mexico, Albuquerque, New Mexico.
https://rosap.ntl.bts.gov/view/dot/12199

- Protocol: DOT Central New Mexico Scenario Planning
- Specific Method: Exposure/hazard mapping; scenario planning
- Evaluation Scale(s): Spatial – regional
- Resource(s): Transportation and land use
- Climate Factors/Hazards: Erosion, flooding, temperature/heat, and precipitation/drought
- Location: Central New Mexico
- Notes: This report summarizes how today's planning decisions have the potential to affect central New Mexico's resilience to climate.

13. Andrew, J., E. Simmons, and B. Rasmussen. 2015. Integration plan for the Mid-Region Council of Governments central New Mexico climate change scenario planning project. DOT-VNTSC-FHWA-15-14. Prepared by U.S. DOT Volpe Center with FHWA, Washington, D.C. https://rosap.ntl.bts.gov/view/dot/12216

- Protocol: DOT Central New Mexico Scenario Planning
- Specific Method: Exposure/hazard mapping; scenario planning
- Evaluation Scale(s): Spatial – regional
- Resource(s): Transportation and land use
- Climate Factors/Hazards: Erosion, flooding, temperature/heat, and precipitation/drought
- Location: Central New Mexico
- Notes: This document provides strategies that MRCOG (and partners) can implement over the next five years to adapt regional policies, programs, and data collection procedures to further the goals of environmental protection, climate change mitigation, climate change adaptation, and resiliency. This plan focuses on the following policy areas: transportation climate-change adaptation assessment, incentivizing transit-oriented activity centers, regional support for travel demand management, open space preservation programs and policies, and green infrastructure investments change impacts in the year 2040 (as part of the CCSP in central New Mexico).

14. Lee, S., M. Tremble, J. Vaivai, G. Rowangould, T. Mohammad, and A. Poorfakhraei. 2015. Central New Mexico climate change scenario planning project: final report. Prepared on behalf of U.S. DOT Volpe Center, FHWA, and the Middle Rio Grande Council of Governments of New Mexico, Albuquerque, New Mexico. https://rosap.ntl.bts.gov/view/dot/12197

- Protocol: DOT Central New Mexico Scenario Planning
- Specific Method: Exposure/hazard mapping; scenario planning
- Evaluation Scale(s): Spatial – regional

- Resource(s): Transportation and land use
- Climate Factors/Hazards: Erosion, flooding, temperature/heat, and precipitation/drought
- Location: Central New Mexico
- Notes: Final summary report for the DOT Central New Mexico Scenario Planning project.

15. Rasmussen, B.K., J. Andrew, E. Simmons, A. Epstein, P. Colton, and D. Daddio. 2015. Integrating climate change in transportation and land use scenario planning: An example from central New Mexico. DOT-VNTSC-FHWA-15-10. Prepared by U.S. DOT Volpe Center with FHWA, FWS, and BLM, Cambridge, Massachusetts. https://rosap.ntl.bts.gov/view/dot/12190

- Protocol: DOT Central New Mexico Scenario Planning
- Specific Method: Exposure/hazard mapping; scenario planning
- Evaluation Scale(s): Spatial – regional
- Resource(s): Transportation and land use
- Climate Factors/Hazards: Erosion, flooding, temperature/heat, and precipitation/drought
- Location: Central New Mexico
- Notes: This report explains the climate change scenario planning process within the central New Mexico study. In addition, the document provides recommendations on how other agencies can incorporate climate change into land use planning.

16. Simmons, E., P. Colton, E. Alexander, and B. Rasmussen. 2015. Potential climate change impacts and the BLM Rio Puerco field office's transportation system: a technical report. DOT-VNTSC-BLM-15-01. Prepared by U.S. DOT Volpe Center for BLM, Cambridge, Massachusetts. https://rosap.ntl.bts.gov/view/dot/12171

- Protocol: DOT Central New Mexico Scenario Planning
- Specific Method: Exposure/hazard mapping; scenario planning
- Evaluation Scale(s): Spatial – regional
- Resource(s): Transportation and land use
- Climate Factors/Hazards: Erosion, flooding, temperature/heat, and precipitation/drought
- Location: Central New Mexico
- Notes: This report describes potential climate change impacts in central New Mexico and possible implications for the Rio Puerco Field Office transportation system. In addition, the report suggests ways in which BLM can incorporate climate change adaptation into transportation planning, and opportunities for climate change mitigation. Potential impacts of climate change discussed: flood risk, drought and water availability, wildfire risk, and impacts to natural resources.

Appendix C: Evaluated Risk Assessments

Canada's Public Infrastructure Engineering Vulnerability Committee (PIEVC – 2008)

17. Canadian Council of Professional Engineers. 2008. Adapting to climate change: Canada's first national engineering vulnerability assessment of public infrastructure, Elgin, Ottawa. https://www.toolkit.bc.ca/resource/adapting-climate-change-canadas-first-national-engineering-vulnerability-assessment-public-infrastru

- Protocol: PIEVC
- Specific Method: Risk = probability x severity
- Evaluation Scale(s): Variable
- Resource(s): Infrastructure and transportation
- Climate Factors/Hazards: Sea-level rise, flooding, temperature/heat, precipitation/drought, wind, freeze/thaw, and severe weather
- Location: Canada
- Notes: Summary protocol document: summarized an engineering vulnerability assessment of four Canadian public infrastructure categories: stormwater and wastewater, water resources, roads and associated structures, and buildings. Vulnerability was rated qualitatively (to different climate and environmental factors) using professional judgment (engineering and operational). Different case studies considered different time frames, but commonly 2020, 2050, and 2080. The PIEVC is referred to as the "Engineering Vulnerability Assessment Protocol" and has five primary steps: 1) Project Definition, 2) Data Gathering, 3) Vulnerability Assessment, 4) Indicator Analysis, and 5) Recommendation. Step 3 is the actual vulnerability assessment, which is a qualitative assessment in which professional judgement is used to determine the likely effect of climate factors on building components. The protocol uses a probability and severity scale to calculate the priority of the effect of climate change factors on each building component (0 to 7 scale). From these two scales, a total "priority of climate change affect" was calculated.

18. Genivar Consultants. 2010. National engineering vulnerability assessment of public infrastructure to climate change. Toronto and region conservation authority flood control dam water resources infrastructure assessment. MA-09-360-00-MA, Markham, Ontario. http://www.trca.on.ca/dotAsset/105187.pdf

- Protocol: PIEVC
- Specific Method: Risk = probability x severity
- Evaluation Scale(s): Spatial – regional; Infrastructure – component
- Resource(s): 3 River Dams
- Climate Factors/Hazards: Temperature, precipitation, extreme weather (lightning, hail, wind, tornado), drought, and hurricanes.

- Location: Toronto, Canada
- Notes: This study includes a vulnerability assessment (using PIEVC protocol) of facilities to current climate (existing and/or historical conditions), as well as vulnerability to future climate change at the 2050-time horizon. Part of this included a risk/vulnerability assessment (defined by experts with site-specific knowledge) and an engineering analysis.

19. Felio, G. 2015. Vulnerability and adaptation of transportation infrastructure to climate change. Paper prepared for presentation at the Risk Assessment and Vulnerability of Mobility session of the 2015 Conference of the Transportation Association of Canada. Charlottetown, Prince Edward Island. http://conf.tac-atc.ca/english/annualconference/tac2015/s13/felio.pdf

- Protocol: PIEVC
- Specific Method: Risk = probability x severity
- Evaluation Scale(s): Variable
- Resource(s): Infrastructure
- Climate Factors/Hazards: Variable
- Location: Canada
- Notes: This document summarizes the processes and methodologies used by agencies and municipalities in Canada to identify climate change infrastructure vulnerabilities and risks as well as adaptation solutions. It focuses on the Engineers Canada's PIEVC Protocol, which evaluates the climate change vulnerability of infrastructure.

Australian Capital Territory (ACT) Infrastructure Vulnerability (2010)

20. AECOM. 2010. Human settlement vulnerability and adaptive capacity assessment, spatial plan evaluation. Prepared for ACT Planning and Land Authority by AECOM Australia Pty Ltd, Canberra, Australia.

- Protocol: ACT Infrastructure Vulnerability
- Specific Method: Sectoral vulnerability = risk (exposure + sensitivity [generic and risk specific] + adaptive capacity (generic and risk specific)
- Evaluation Scale(s): Spatial – community; Infrastructure – systems
- Resource(s): Infrastructure, developed areas/population
- Climate Factors/Hazards: Flooding, temperature/heat, precipitation/drought, fires
- Location: Australia
- Notes: This document assessed the vulnerability of Australian Capital Territory's human settlement to multiple factors of climate change.

21. SGS Economics and Planning. 2010. Spatial plan evaluation – urban form scenarios – adaptation and mitigation inventions. Prepared for ACT Planning and Land Authority, in association with Simpson and Wilson Architecture and Urban Design and Kenesis, Canberra, Australia.

- Protocol: ACT Infrastructure Vulnerability
- Specific Method: Adaptation and Mitigation. Sectoral vulnerability = risk (exposure + sensitivity [generic and risk specific] + adaptive capacity (generic and risk specific).
- Evaluation Scale(s): Spatial – community; Infrastructure – systems
- Resource(s): Infrastructure, developed areas/population
- Climate Factors/Hazards: Flooding, temperature/heat, precipitation/drought, fires
- Location: Australia
- Notes: This document summarizes the mitigation of and adaptation to climate change in Canberra, which follows up assessment of the vulnerability and adaptive capacity of the urban areas.

22. AECOM. 2012. Climate change vulnerability assessment framework for infrastructure: Discussion paper. Prepared for and in collaboration with ACT Chief Minister's Department by AECOM Australia Pty Ltd, Canberra, Australia. http://www.cmd.act.gov.au/__data/assets/pdf_file/0018/302436/Climate_Change_Vulnerability_Assessment_Framework_for_Infrastructure.pdf

- Protocol: ACT Infrastructure Vulnerability
- Specific Method: Sectoral vulnerability = risk (exposure + sensitivity [generic and risk specific] + adaptive capacity (generic and risk specific)
- Evaluation Scale(s): Variable
- Resource(s): Infrastructure, developed areas/population
- Climate Factors/Hazards: Flooding, temperature/heat, precipitation/drought, and fires
- Location: Australia
- Notes: Summary protocol document: this document summarizes the framework used for assessing the vulnerability of Australian Capital Territory's infrastructure to climate change. Vulnerability was analyzed as a function of risk (exposure and sensitivity) and adaptive capacity. The scoring for each element/factor was combined and weighted depending on data availability, as well as its ability to represent the element of the considered risk. Landscape-scale maps were a product of this framework (not asset-by-asset analysis).

Alaska Long Range Transportation Plan Risk Assessment (2016)

23. National Park Service (NPS). 2016b. Park road assessment workshop summary, Denali National Park and Preserve (DENA). November 29-December 1, 2016, Anchorage, Alaska.

- Protocol: Alaska Long Range Transportation Plan Risk Assessment
- Specific Method: Risk = probability x impact
- Evaluation Scale(s): Spatial – park; Infrastructure – systems
- Resource(s): Park road

- Climate Factors/Hazards: Landslides, permafrost subsidence
- Location: Denali NP Alaska
- Notes: Summary of a workshop on risk assessment for Denali Park Road, a 92-mile corridor that provides the only access to the park and preserve. NPS staff worked with FHWA to complete a risk analysis of Denali Park Road, which included geohazards mapping (distribution, susceptibility, and risk of landslides and permafrost subsidence), testing of the Unstable Slope Management Protocol rating criteria, and analyses/recommendations with respect to other risks to the road (alteration of facility assets/standards, revised vehicle specifications, changes in maintenance, operations and park management) for incorporation into the park's long range transportation plan.

24. National Park Service (NPS). 2017a. Alaska collaborative long range transportation plan risk management workshop. December 12-14, 2017, Anchorage, Alaska.

- Protocol: Alaska Long Range Transportation Plan Risk Assessment
- Specific Method: Risk = probability x impact
- Evaluation Scale(s): Spatial – state; Infrastructure – systems
- Resource(s): Transportation assets
- Climate Factors/Hazards: Landslides, permafrost subsidence
- Location: Alaska
- Notes: This workshop focuses on the long-range transportation plan for Alaska, and is meant to 1) describe all types of risk exposure (e.g., geophysical hazards, alteration of facility assets, changes in maintenance or operations), 2) evaluate each risk to examine qualitative impacts/responses, and 3) strategize how the final products will be completed.

Individual Studies

25. Brooks, K.A., and J.H. Clark. 2015. Evaluating vulnerability of critical state park infrastructure caused by extreme weather events: A Tennessee application. Risk Management 17(4):298–328. https://link.springer.com/article/10.1057/rm.2015.17

- Protocol: n/a
- Specific Method: Risk = frequency x impact
- Evaluation Scale(s): Spatial – county; Infrastructure – systems
- Resource(s): Infrastructure categories
- Climate Factors/Hazards: Tornadoes, lightning, hydrologic, thunderstorm, wind, hail, Winter event, cold, drought, and heat
- Location: Tennessee
- Notes: This project calculated vulnerability of infrastructure categories (dining and lodging, camping and recreation, operations, and retail) to extreme weather events (tornadoes, lightning, hydrologic, wind, drought, heat, etc.) within the state of Tennessee. Vulnerability

was calculated on a county-by-county basis. This vulnerability assessment methodology focused on infrastructure categories (not asset-specific) at the county level. Generally, the annual expected frequency of each type of weather event was multiplied by its impact scores according to the infrastructure type. The impact scores for each event/infrastructure combination (e.g., Hydrologic Impact Score for Operations) were calculated in a previous study by the same authors.

26. Jamie Caplan Consulting. 2015. Territory of American Samoa, multi-hazard mitigation plan. Prepared for the American Samoa Governor's Office, American Samoa Territorial Hazard Mitigation Council, Northampton, Massachusetts. https://www.wsspc.org/wp-content/uploads/2016/07/AmericanSamoa_mitigationplan15-20.pdf

- Protocol: n/a
- Specific Method: Risk = probability + impact + spatial extent + warning time + duration
- Evaluation Scale(s): Spatial – site; Infrastructure –asset
- Resource(s): Critical facilities and infrastructure
- Climate Factors/Hazards: Climate change (including sea-level rise), coastal erosion, drought, earthquake, floods, high surf, landslide, lightning, soil hazards (including sinkholes, subsidence, and expansion), tropical cyclones (including storm surge and high wind storms), tsunamis, volcano, and wildfire.
- Notes: This study examined the vulnerability of current and future populations and structures (including critical facilities and infrastructure) to various natural hazards.
- The vulnerability of each hazard was qualitatively evaluated based on research related to the hazard location, previous occurrence, extent, and probability. When possible, hazard and infrastructure mapping was conducted (e.g., comparing location of structure to FEMA flood zones), followed by estimations for potential losses (e.g., number of buildings with high risk to earthquakes due to soil type).

27. Historic Environment Scotland (HES). 2017. A climate change and risk assessment of the properties in care of Historic Environment Scotland. Prepared by the Historic Environment Scotland Climate Change Team with contributions from E. Tracey (British Geological Survey). Principal authors: D. Harkin, M. Davies, and E. Hyslop (Historic Environment Scotland), Edinburgh, Scotland. https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=55d8dde6-3b68-444e-b6f2-a866011d129a

- Protocol: n/a
- Specific Method: Risk = likelihood x consequence
- Evaluation Scale(s): Spatial – site; Infrastructure - asset
- Resource(s): Historic properties/infrastructure
- Climate Factors/Hazards: Flooding, erosion, slope instability
- Location: Scotland

- Notes: This document summarizes the protocol and results of a climate change risk assessment of historic properties in Scotland. Used GIS to map natural hazard risk (exposure to a range of environmental threat that have the potential to cause damage to the asset and its cultural significance). Spatial analysis of hazards for likelihood, impact considered property type, staffing, visitor access. Focuses on 6 factors related to climate change: fluvial flooding, pluvial flooding, coastal flooding, coastal erosion, groundwater flooding, and slope instability.

Appendix D: Evaluated Indicator-Based Vulnerability Assessments

FHWA Gulf Coast Study (2008)

28. Climate Change Science Program (CCSP). 2008. Impacts of climate change and variability on transportation systems and infrastructure. The Gulf Coast Study, phase I. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Savonis, M. J., V.R. Burkett, and J.R. Potter, editors. DOT, Washington, D.C. http://www.iooc.us/wp-content/uploads/2010/09/Impacts-of-Climate-Change-and-Variability-on-Transportation-Systems-and-Infrastructure-Gulf-Coast-Study-Phase-I.pdf

- Protocol: FHWA Gulf Coast Study
- Specific Method(s): Vulnerability = exposure + sensitivity + adaptive capacity. Criticality also assessed
- Evaluation Scale: Spatial – site; Infrastructure – asset
- Resource(s): Transportation
- Climate Factors/Hazards: Sea-level rise, storm surge, temperature/heat, precipitation/drought, and wind
- Location: Mobile, Alabama (Central Gulf Coast)
- Notes: U.S DOT - FHWA project that produced tools and lessons learned for assessing vulnerabilities and building resilience to climate change in the transportation sector, beginning on the Central Gulf Coast. The goal of this project was to better understand climate change impacts on transportation infrastructure and identify potential adaptation strategies. In addition, the study developed methods for evaluating vulnerability and adaptation measures that could be used by other transportation agencies; these methods were tested on the transportation system in Mobile, Alabama as a pilot project. This project uses an indicator-based methodology where climate change vulnerability is calculated as a combination of exposure, sensitivity, and adaptive capacity. Criticality is also evaluated, prior to the vulnerability assessment. Climate change factors considered include: temperature change, precipitation changes, sea-level rise, storm surge, and wind. This document presents the findings of Phase 1 of the Gulf Coast Study. The main objective of Phase 1 was to conduct a preliminary assessment of the risks and impacts of climate change on transportation systems and infrastructure.

29. ICF International and PB Americas. 2011. Impacts of climate change and variability on transportation systems and infrastructure: The Gulf Coast Study, phase 2. Task 1: Assessing infrastructure for criticality in Mobile, AL. FHWA-HEP-11-029. Prepared for U.S. DOT Center for Climate Change and Environmental Forecasting. Project Managed by Office of Planning, Environment, and Realty, FHWA, Washington, D.C. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/phase2_task1/gulfcoast2.pdf

- Protocol: FHWA Gulf Coast Study
- Specific Method(s): Vulnerability = exposure + sensitivity + adaptive capacity. Criticality also assessed
- Evaluation Scale: Spatial – site; Infrastructure – asset
- Resource(s): Transportation
- Climate Factors/Hazards: Sea-level rise, storm surge, temperature/heat, precipitation/drought, and wind
- Location: Mobile, Alabama (Central Gulf Coast)
- Notes: This report summarizes the methodology and findings of Task 1 of Phase 2 of the Gulf Coast Study, which identified the transportation infrastructure components most critical to the Mobile region.

30. ICF International. 2013b. Impacts of climate change and variability on transportation systems and infrastructure. The Gulf Coast Study, phase 2, task 2. Climate variability and change in Mobile, Alabama. FHWA-HEP-12-053. Contributions from: South Coast Engineers, Texas Tech University, USGS, and PB Americas. Prepared for the U.S. DOT Center for Climate Change and Environmental Forecasting. Project Managed by Office of Planning, Environment, and Realty, FHWA, Washington, D.C.
https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/phase2_task2/mobile_variability/task2_main.pdf

- Protocol: FHWA Gulf Coast Study
- Specific Method(s): Vulnerability = exposure + sensitivity + adaptive capacity. Criticality also assessed
- Evaluation Scale: Spatial – site; Infrastructure – asset
- Resource(s): Transportation
- Climate Factors/Hazards: Sea-level rise, storm surge, temperature/heat, precipitation/drought, and wind
- Location: Mobile, Alabama (Central Gulf Coast)
- Notes: This report summarizes Task 2 of Phase 2 of the Gulf Coast Study, and explores potential changes in five primary climate variables: temperature, precipitation, streamflow, sea-level rise, and storm surge in Mobile, AL.

31. ICF International. 2014a. Impacts of climate change and variability on transportation systems and infrastructure. The Gulf Coast Study, phase 2, task 3.1. Screening for vulnerability. FHWA-HEP-14-033. Prepared for the U.S. DOT Center for Climate Change and Environmental Forecasting. Project Managed by: Office of Planning, Environment, and Realty, FHWA, Washington, D.C.
https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/phase2_task3/task_3.1/phase2task3.pdf

- Protocol: FHWA Gulf Coast Study
- Specific Method(s): Vulnerability = exposure + sensitivity + adaptive capacity. Criticality also assessed
- Evaluation Scale: Spatial – site; Infrastructure – asset
- Resource(s): Transportation
- Climate Factors/Hazards: Sea-level rise, storm surge, temperature/heat, precipitation/drought, and wind
- Location: Mobile, Alabama (Central Gulf Coast)
- Notes: This report describes Task 3.1 of Phase 2 of the Gulf Coast Study: the methodology and findings of the high-level vulnerability assessment of the transport system in Mobile, AL.

32. ICF International. 2014b. Assessing transportation vulnerability to climate change: Synthesis of lessons learned and methods applied. FHWA-HEP-15-007. Prepared for the U.S. DOT Center for Climate Change and Environmental Forecasting. Project Managed by Office of Planning, Environment, and Realty, FHWA, Washington, D.C. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/phase2_task6/fhwahep15007.pdf

- Protocol: FHWA Gulf Coast Study
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity. Criticality also assessed
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Transportation
- Climate Factors/Hazards: Sea-level rise, storm surge, temperature/heat, precipitation/drought, and wind
- Location: Mobile, Alabama (Central Gulf Coast)
- Notes: This report synthesized Phase 2 of the Gulf Coast Study, including: 1) Evaluating Criticality, 2) Gather and Process Climate Information, 3) Assess Vulnerability, 4) Develop Tools and Resources, and 5) Coordinate with Planning Authorities and the Public.

33. Parsons Brinckerhoff and ICF International. 2014. The Gulf Coast Study, phase 2, task 3.2. Engineering assessments of climate change impacts and adaptation measures. FHWA-HEP-15-004. Prepared for the U.S. DOT Center for Climate Change and Environmental Forecasting. Project Managed by Office of Planning, Environment, and Realty, FHWA. Contributions from South Coast Engineers, Washington, D.C. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/phase2_task3/task_3.2/task2phase3.pdf

- Protocol: FHWA Gulf Coast Study

- Specific Method(s): Vulnerability = exposure + sensitivity + adaptive capacity. Criticality also assessed
- Evaluation Scale: Spatial – site; Infrastructure – asset
- Resource(s): Transportation
- Climate Factors/Hazards: Sea-level rise, storm surge, temperature/heat, precipitation/drought, and wind
- Location: Mobile, Alabama (Central Gulf Coast)
- Notes: This report discusses a series of engineering assessments on specific transportation facilities in Mobile, AL. In addition, this study evaluated if facilities might be vulnerable to projected changes in climate, and potential adaptation measures to mitigate those vulnerabilities.

FHWA Climate Change Pilots, 2010-2011

34. Federal Highway Administration (FWHA). 2010. Assessing vulnerability and risk of climate change effects on transportation infrastructure: pilot of the conceptual, website. Accessed March 2018. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2010-2011_pilots/conceptual_model62410.cfm

- Protocol: FHWA Climate Change Pilots, 2010-2011
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity
- Evaluation Scale(s): Variable
- Resource(s): Transportation infrastructure
- Climate Factors/Hazards: Variable
- Location: Variable
- Notes: Between 2010 and 2011, multiple pilot studies were conducted based on a conceptual model for assessing vulnerability to climate change. This conceptual model has three primary components: 1) develop inventory of assets, 2) gather climate information, and 3) assess the risk to assets and the transportation system as a whole from projected climate change. The first component includes compiling information on all assets which may be evaluated, including the significance and priority of each to prioritize the assessment. The second component includes assessing the risk of each climate stressor identified (the potential for an unwanted outcome). The vulnerability assessment protocol (and the associated pilot studies) evaluated vulnerability on the asset-level using an indicator-based methodology (rating exposure, sensitivity, and adaptive capacity). Evaluating criticality and risk were also key components to the model.

35. North Jersey Transportation Planning Authority (NJTPA). 2011. FHWA climate change vulnerability assessment pilot project. FHWA-HEP-14-005, Newark, New Jersey. https://www.fhwa.dot.gov/environment/sustainability/resilience/case_studies/new_jersey/new_jersey.pdf

- Protocol: FHWA Climate Change Pilots, 2010-2011
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Transportation infrastructure
- Climate Factors/Hazards: Sea-level rise, storm surge, inland flooding, temperature, and precipitation
- Location: New Jersey
- Notes: Assessed the sea-level rise, storm surge, inland flooding, temperature, and precipitation vulnerability (V = E + S + AC) of roads, bridges, rail, airports, wetlands, tunnels, marinas, and ferry terminals. Criticality was determined using the following factors: importance of the destinations (identified based on jobs and population density), magnitude of connection (identified by traffic volume), and emergency function of routes (identified primarily by presence of coastal evacuation routes). Scored on a low/medium, high, and extreme criticality. Exposure was calculated by overlying location of assets with SLR, storm surge, and inland flooding scenarios in GIS. Sensitivity was determined by an asset's threshold failure and adaptive capacity by how easily as asset could be restored if the asset was disrupted by a weather event (both were obtained from interviews).

36. San Francisco Bay Conservation and Development Commission (BCDC) and Metropolitan Transportation Commission (MTC). 2011. Adapting to rising tides: Transportation vulnerability and risk assessment pilot project, briefing book. San Francisco, California. https://mtc.ca.gov/sites/default/files/Rising_Tides_Briefing_Book.pdf

- Protocol: FHWA Climate Change Pilots, 2010-2011
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity; Risk = likelihood x impact
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Transportation infrastructure
- Climate Factors/Hazards: Sea-level rise and seismicity
- Location: San Francisco
- Notes: Assessed the sea-level rise (V = E + S + AC, and risk) of roads, transit, transportation facilities, and shoreline assets. Exposure was calculated using two scenarios (mid and end of century) and whether an asset was modeled to be inundated. Sensitivity was calculated by a combination of level of use, age of facility, maintenance, etc. Remaining service life was NOT used for sensitivity, authors argued that data on remaining service life does not provide a conclusive indication of sensitivity. Sensitivity were only compared to other similar assets (such as the same asset type, e.g., roads were only compared to roads). Adaptive capacity was determined whether there was an alternative route that could provide a similar level of functionality.

37. SSFM International. 2011. Transportation asset climate change risk assessment report. Oahu Prepared for Oahu Metropolitan Planning Organization and the FHWA, Honolulu, Hawaii. http://www.oahumpo.org/wp-content/uploads/2013/01/CC_Report_FINAL_Nov_2011.pdf

- Protocol: FHWA Climate Change Pilots, 2010-2011
- Specific Method: General Risk = likelihood + magnitude (vulnerability) + consequence (impact)
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Transportation infrastructure
- Climate Factors/Hazards: Sea-level rise, storm surge, precipitation, wind, and temperature
- Location: Oahu, Hawaii
- Notes: Assessed the sea-level rise, storm surge, precipitation, wind, and temperature vulnerability (Risk = likelihood, magnitude, consequence) of roads, bridges, and tunnels. Was a qualitative assessment, where risk (vulnerability + impact) was estimated (low, moderate, high) for each asset/group of assets.

38. Virginia Department of Transportation (VDOT). 2011. Assessing vulnerability and risk of climate change effects on transportation infrastructure. Hampton Roads Virginia Pilot, Richmond, Virginia.
https://www.cakex.org/sites/default/files/documents/FHWA_Assessing%20%20Vulnerability%20%20and%20%20Risk%20%20of%20%20Climate%20%20Change%20Effects%20on%20Transportation%20Infrastructure_2012.pdf

- Protocol: FHWA Climate Change Pilots, 2010-2011
- Specific Method: General vulnerability discussions
- Evaluation Scale(s): Spatial – regional; Infrastructure – asset
- Resource(s): Transportation infrastructure
- Climate Factors/Hazards: Sea-level rise, storm surge, temperature, and climate change
- Location: Hampton Roads, Virginia
- Notes: Produced model for transportation infrastructure regarding: 1) interactions between climate change and other factors, 2) connection between scenarios and strategic planning, and 3) prioritization of resources. No specific VA method was discussed.

39. Washington State Department of Transportation (WSDOT). 2011. Climate impacts vulnerability assessment, report. Prepared by the Washington State DOT for submittal to the FHWA, Olympia, Washington. https://toolkit.climate.gov/reports/washington-state-dot-climate-impacts-vulnerability-assessment

- Protocol: FHWA Climate Change Pilots, 2010-2011
- Specific Method: Vulnerability = criticality + impact

- Evaluation Scale(s): Spatial – site; Unfractured – asset
- Resource(s): Transportation infrastructure
- Climate Factors/Hazards: Sea-level rise, storm surge, temperature, and climate change
- Location: Washington State
- Notes: Assessed the sea-level rise, precipitation, temperature and fire vulnerability (criticality + impact) of roads, bridges, and tunnels; was a qualitative assessment.

NPS Facilities Adaptation (prepared by ICF - 2012)

40. ICF International. 2012a. Facilities adaptation to climate change impacts in coastal areas: workshop findings for Pu`uhonua O Hōnaunau National Historic Park, September 2012. Prepared for the NPS, Washington, D.C.

- Protocol: NPS Facilities Adaptation (prepared by ICF)
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation
- Climate Factors/Hazards: Coastal hazards (elevation, soil erosion, vegetation, tsunami risk, and dune protection)
- Location: Pu`uhonua O Hōnaunau National Historic Park (PUHO), Hawaii
- Notes: The study uses an asset-specific indicator-based VA where vulnerability is a combination of exposure, sensitivity, and adaptive capacity. Exposure was calculated using a combination of indicators, depending on the hazards present (e.g., elevation, soil erosion potential, vegetation, tsunami risk, dune protection), sensitivity was calculated using the asset's condition rating (from the NPS facilities database), and adaptive capacity was calculated using the asset's replacement value (from the NPS facilities database). Exposure comprised 50% of the total vulnerability score, and sensitivity and adaptive capacity each made up 25% of the total score.

41. ICF International. 2012b. Facilities adaptation to climate change impacts in coastal areas: workshop findings for Assateague Island National Seashore, December 2012. Prepared for the NPS, Washington, D.C.

- Protocol: NPS Facilities Adaptation (prepared by ICF)
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation
- Climate Factors/Hazards: Coastal hazards (elevation, soil erosion, vegetation, tsunami risk, and dune protection)
- Location: Assateague Island National Seashore (ASIS), Maryland and Virginia

- Notes: The study uses an asset-specific indicator-based VA where vulnerability is a combination of exposure, sensitivity, and adaptive capacity. Exposure was calculated using a combination of several indicators, depending on the hazards present (e.g., elevation, soil erosion potential, vegetation, tsunami risk, dune protection), sensitivity was calculated using the asset's condition rating (from the NPS facilities database), and adaptive capacity was calculated using the asset's replacement value (from the NPS facilities database). Exposure was 50% of the total vulnerability score, and sensitivity and adaptive capacity each made up 25% of the total score.

42. ICF International. 2013a. Facilities adaptation to climate change impacts in coastal areas: Workshop findings for Assateague Island National Seashore, with addendum on post-Hurricane Sandy assessment, April 2013. Prepared for the NPS, Washington, D.C.

- Protocol: NPS Facilities Adaptation (prepared by ICF)
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation
- Climate Factors/Hazards: Coastal hazards (elevation, soil erosion, vegetation, tsunami risk, and dune protection)
- Location: Assateague Island National Seashore (ASIS), Maryland and Virginia
- Notes: The document updated the results for the previous ASIS study to include the post-Hurricane Sandy Assessment.

FHWA Climate Change Pilots, 2013-2015

43. Federal Highway Administration (FHWA). 2012. Climate change and extreme weather vulnerability assessment framework. FHWA-HEP-13-005. Department of Transportation, Washington, D.C.
https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/vulnerability_assessment_framework/fhwahep13005.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity; Risk/vulnerability = Criticality X potential impact
- Evaluation Scale(s): Asset-specific
- Resource(s): Infrastructure and transportation
- Climate Factors/Hazards: Variable
- Location: Variable
- Notes: After the 2010-2011 pilots were completed using the initial conceptual model, the model was revised based on lessons learned. This 2012 document outlines the revised framework for climate change and extreme weather vulnerability assessments. The following

case studies (Case Studies 1 -19) used this newly revised framework. This framework consists of three primary components: 1) defining objectives and scope; 2) assessing vulnerability; and 3) integrating vulnerability into decision-making. This vulnerability assessment utilizes asset-level indicator-based vulnerability methodology (rating exposure, sensitivity, and adaptive capacity). In many cases, criticality was used to narrow assets down for vulnerability analysis. The actual scoring of vulnerability ranged within the case studies, from more quantitative Geographic Information Systems-based computations to qualitative stakeholder and expert opinion analysis. A number of these case studies used the U.S. DOT Vulnerability Assessment Scoring Tool (VAST).

44. Almodovar-Rosario, N. and C. Dorney. 2014. MnDOT flash flood vulnerability and adaptation assessment pilot project, final report. Prepared by Parsons Brinkerhoff and Catalysis Adaptation Partners for Minnesota DOT and FHWA, Baltimore, Maryland. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/minnesota/final_report/mndotreport.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Transportation assets
- Climate Factors/Hazards: Flash flood vulnerability
- Location: Minnesota
- Notes: Analyzed the flash flood vulnerability of transportation assets, used a number of indicators for the metrics of vulnerability: exposure, sensitivity, and adaptive capacity. Calculated risk by vulnerability x criticality.

45. Bonham-Carter, C., K. May, C. Thomas, A. Sudhalkar, B. Fish, A. Boone, M. Mak, J. Mull, J. DeFlorio, and J. Dempster. 2014. Climate change and extreme weather adaptation options for transportation assets in the Bay Area pilot project. Prepared by AECOM, Cambridge Systematics, and Avila & Associates for the Metropolitan Transportation Commission and FHWA, San Francisco, California. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/mtc/final_report/mtcfinal.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Sea-level rise inundation scenarios used for exposure analysis; Qualitative vulnerability (physical, functional, informational, and governance factors considered)
- Evaluation Scales(s): Spatial – site; Infrastructure – asset
- Resource(s): Transportation assets (roads, rails, and transit)
- Climate Factors/Hazards: Sea-level rise and storm surge/wind
- Location: San Francisco

- Notes: This study focused on sea-level rise and storm/wind vulnerability of core transportation assets in three focus areas within Alameda County sub-region.

46. Hogan, M., D. Elder, and S. Molden. 2014. Climate change and extreme weather vulnerability pilot project. Vulnerability assessment of bridges and culverts to inland flooding and extreme rain. Connecticut Department of Transportation, Newington, Connecticut. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/connecticut/final_report/ctclimatepilot.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Criticality; vulnerability calculated with hydrologic and hydraulic evaluations
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Bridges and culverts
- Climate Factors/Hazards: Inland flooding and extreme precipitation
- Location: Connecticut
- Notes: Vulnerability assessment bridges and culverts to inland flooding and extreme rain. Assessed criticality using hydraulic, spatial, and social factors.

47. DeFlorio, J., C. Goodison, A. Wynne, M. Flynn, E. Henry, K. Bolter, M. Cahill, R. Clarendon, and A. Yeh. 2014. Hillsborough County MPO: Vulnerability assessment and adaptation pilot project. Prepared by Cambridge Systematics for Hillsborough County Metropolitan Planning Organization for Transportation, the Hillsborough County City-County Planning Commission, and FHWA, Tampa, Florida. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/florida/final_report/florida.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Transportation assets
- Climate Factors/Hazards: Sea-level rise, storm surge, inland flooding
- Location: Hillsborough County, Florida
- Notes: Assessed the sea-level rise, storm surge, and flooding vulnerability of transportation assets. Exposure was GIS based, sensitivity was qualitative with engineering experts. Adaptive capacity was based on functionality (only way to get somewhere). Criticality was quantitatively determined.

48. GHD. 2014. District 1 climate change vulnerability assessment and pilot studies: FHWA climate resilience pilot final report. Prepared for Caltrans and Humboldt County Association of Governments. 69p. http://www.dot.ca.gov/hq/tpp/offices/orip/climate_change/documents/ccps.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Vulnerability = criticality (importance) x potential impact (exposure, sensitivity, and adaptive capacity); adaptation options
- Evaluation Scale(s): Spatial – regional; Infrastructure – systems
- Resource(s): Infrastructure and transportation (road segments)
- Climate Factors/Hazards: Temperature, precipitation, runoff, fire, landslides, erosion, and sea-level rise and storm flooding
- Location: Northern California
- Notes: Assessed transportation (bridges, storm water facilities, rest areas, etc.) vulnerability (criticality x potential for impact), and adaptation. Hazards: temperature, precipitation, runoff, fire, landslides, erosion, and sea-level rise and storm flooding. Used experts to score criticality based on 40 factors, assessed exposure using spatial analysis of historical events and climate factors. Adaptation options were identified and evaluated based on a number of factors including cost, effectiveness, flexibility, benefits, and social and environmental factors.

49. Maryland State Highway Administration and Santec Consulting Services. 2014. Maryland State Highway Administration climate change adaptation plan with detailed vulnerability assessment. Prepared by Maryland State Highway Administration, Santec, and Salisbury University Eastern Shore Regional GIS Cooperative for FHWA, Baltimore, Maryland. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/maryland/final_report/mdpilot.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Bridges, roadways, and culverts/drainages
- Climate Factors/Hazards: Sea-level rise, storm surge, and increase precipitation intensity
- Location: Maryland
- Notes: Assessed vulnerability of transportation assets to sea-level rise, storm surge, and increased precipitation in two counties in Maryland. Used a three-tiered concept:1) desktop analysis to prioritize assets, 2) conduct a detailed VA of asset highlighted in tier 1, and 3) conduct a site-specific analysis for vulnerability locations, using detailed hydraulic modeling and engineering. Tier 2 used the VAST to select indicators for the vulnerability metrics.

50. Merrill, S. and J. Gates. 2014. Integrating storm surge and sea level rise vulnerability assessments and criticality analyses into asset management at MaineDOT. Prepared by Catalysis Adaptation Partners and Maine DOT for FHWA, Freeport and Augusta, Maine.

https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/maine/final_report/maine.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Qualitative vulnerability and criticality
- Evaluation Scale(s): Spatial – asset site, Infrastructure – asset
- Resource(s): Infrastructure and transportation
- Climate Factors/Hazards: Sea-level rise and storm surge
- Location: Maine
- Notes: This study focused on engineering designs and cost analysis for a few high priority, high vulnerability assets in 3 towns in Maine. The vulnerability and criticality portion of the analysis was done qualitatively based on past flooding, maintenance, and prioritization.

51. Michigan Department of Transportation (MDOT), Cambridge Systematics, and Status Consulting. 2014. Michigan DOT climate vulnerability assessment pilot project, final report. Prepared for FHWA, Lansing, Michigan. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/michigan/final_report/mdotfiinalreport.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Exposure
- Evaluation Scale(s): Spatial – asset site
- Resource(s): Transportation assets
- Climate Factors/Hazards: Precipitation and temperature
- Location: Michigan
- Notes: Analyzed the exposure (as a proxy for vulnerability) of transportation assets to climate stressors – precipitation and temperature.

52. Oregon Department of Transportation (ODOT). 2014. Climate change vulnerability assessment and adaptation options study. Prepared for FHWA, Salem, Oregon. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/oregon/final_report/odotreport.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity (qualitatively ranked vulnerability - resilience)
- Evaluation Scale(s): Spatial – asset site (road corridors); Infrastructure – asset (road corridor)
- Resource(s): Transportation assets
- Climate Factors/Hazards: Temperature, precipitation, sea-level rise, and storm surge

- Location: North Oregon coast
- Notes: Analyzed the climate change (temperature, precipitation, sea-level rise, and storm surge) vulnerability of transportation assets (state owned highways, bridges, culverts, and maintenance facilities). Considered the exposure, sensitivity, and adaptive capacity of assets – rated of vulnerable based workshop (expert opinion). The study also defined critical assets and developed adaptation strategies.

53. Abkowitz, M., J. Camp, and L. Dundon. 2015. Assessing the vulnerability of Tennessee transportation assets to extreme weather. Prepared by 3 Sigma Consultants for Tennessee DOT and FHWA, Nashville, Tennessee. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/tennessee/final_report/tdot.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Vulnerability = likelihood x consequence
- Evaluation Scale(s): Spatial – county; Infrastructure – asset
- Resource(s): Transportation assets
- Climate Factors/Hazards: Extreme weather (e.g., temperature, wind, tornadoes, hail, lightning, hydrology, drought).
- Location: Tennessee
- Notes: First assessed criticality of transporting asset, then vulnerability (calculated as likelihood and consequence) to extreme weather events. Vulnerability was calculated by multiplying the annual expected frequency of each type of extreme weather event and the impact score for the asset type when exposed to the particular extreme weather event. The impact score was obtained from a survey of expert opinion.

54. Anderson, T., C. Beck, K. Gade, and S. Olmsted. 2015a. Extreme weather vulnerability assessment. Prepared by Cambridge Systematics for Arizona DOT and FHWA, New York, New York. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/arizona/final_report/arizonafinal.pdf

- Protocol: FWHA Climate Change Pilots, 2013-2015
- Specific Method: Qualitative estimate of risk (exposure only)
- Evaluation Scale(s): Spatial – regional
- Resource(s): Infrastructure and transportation
- Climate Factors/Hazards: Extreme heat, freeze-thaw, extreme precipitation, and wildfire.
- Location: Arizona
- Notes: This case study examined climate-related stressors (extreme heat, freeze-thaw, extreme precipitation, and wildfire) of Arizona (Interstate corridor connecting Nogales, Tucson, Phoenix, and Flagstaff) transportation infrastructure and considered how these risk

factors would change in the future. Not asset-specific. Risk of future vulnerability in the next century was evaluated qualitatively based on climate data. This "risk hypothesis" was scored as negative, neutral, uncertain, or positive for each district and climate factor combination. Impact to assets/systems were not estimate (only potential change in each stressor).

55. Anderson, C., D. Claman, and R. Mantilla. 2015b. Iowa's bridge and highway climate change and extreme weather vulnerability assessment pilot. Prepared by the Institute for Transportation, Iowa State University for Iowa DOT and FHWA. HEPN-707, Ames, Iowa. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/iowa/final_report/iowapilot.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Hazard and impact modeling
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Bridges
- Climate Factors/Hazards: Increased precipitation
- Location: Iowa
- Notes: Assessed vulnerability of 6 bridges in two Iowa River Basins using a modeling-based methodology for streamflow and scenarios of climate change. The methodology yielded results that combined historical information and scenario-based design metrics to be used in bridge vulnerability and design.

56. Cambridge Systematics. 2015. Central Texas extreme weather and climate change vulnerability assessment of regional transportation infrastructure. Prepared for the Capital Area Metropolitan Planning Organization, the City of Austin, and FHWA, Austin, Texas. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/campo/final_report/campo.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity
- Evaluation Scale(s) Spatial – county; Infrastructure – asset
- Resource(s): Infrastructure and transportation (road segments)
- Climate Factors/Hazards: Flooding, drought, extreme heat, wildfire, and extreme cold
- Location: Central Texas
- Notes: Assessed the vulnerability of transportation assets (roadways, bridges, rail) to flooding, drought, extreme heat, wildfire, and extreme cold to the year 2040. First assessed criticality, then used VAST. Criticality was assessed qualitatively by expert opinion.

57. Dorney, C., M. Flood, M. Meyer, G. Cornetski, G. Borroni, and J. Lafferty. 2015. South Florida climate change vulnerability assessment and adaptation pilot project. Prepared by Parson

Brinckerhoff for Broward Metropolitan Planning Organization and FHWA, Miami, Florida. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/south_florida/final_report/south_florida_final.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity
- Evaluation Scale(s): Spatial – asset site; Infrastructure – asset
- Resource(s): Transportation assets – roads and rail
- Climate Factors/Hazards: Sea-level rise, storm surge/heavy rainfall inundation
- Location: South Florida
- Notes: This study analyzed the climate change (sea-level rise and storm surge/heavy rainfall inundation) vulnerability of roads and rail links in the region. The study considered exposure (detailed mapping), sensitivity (number and condition of bridges along each road segment), and adaptive capacity (traffic volume and detour lengths).

58. Nelson, D., M. Brown, and J. Levine. 2015. Climate vulnerability and economic assessment for at-risk transportation infrastructure in the Lake Champlain Basin, New York. Prepared by New York DOT and The Nature Conversancy for FHWA, Albany and Keene Valley, New York. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/new_york/final_report/newyork.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Risk = vulnerability x criticality
- Evaluation Scale(s): Spatial – regional; Infrastructure –asset level
- Resource(s): Culverts
- Climate Factors/Hazards: Flooding
- Location: Lake Champlain Basin, New York
- Notes: Analyzed vulnerability, criticality, and risk of culverts to flooding. Vulnerability was calculated by expert opinion.

59. Roalkvam, C.L. 2015. Creating a resilient transportation network in Skagit County: Using flood studies to inform transportation asset management. Prepared by Washington State DOT for FHWA, Olympia, Washington. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/washington/final_report/skagitriverreport.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Exposure/hazard mapping (referred to as vulnerability)
- Evaluation Scale(s): Spatial – asset site (road segments)
- Resource(s): Transportation assets (road segments)
- Climate Factors/Hazards: Extreme flooding

- Location: Skagit County, Washington
- Notes: This document focused on adaptation strategies for transportation assets (road segments) for one basin that that had been previously identified as highly vulnerable. This report includes recommendations and lessons learned to help DOT and regional transportation planning group collaborate across jurisdictions and to create integrated asset management strategies.

60. Winguth, A., J.H. Lee, and Y. Ko. 2015. Climate change/extreme weather vulnerability and risk assessment for transportation infrastructure in Dallas and Tarrant Counties. Prepared by the University of Texas at Arlington for the North Central Texas Council of Governments and FHWA, Arlington, Texas. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/nctcog/final_report/nctogfinal.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Vulnerability = criticality x exposure
- Evaluation Scale(s): Spatial – variable, primarily regional (climate data) and asset-site (flood mapping); Infrastructure – asset level (for criticality)
- Resource(s): Transportation assets
- Climate Factors/Hazards: Flooding and temperature
- Location: North Central Texas
- Notes: Analyzed climate change vulnerability of transportation assets to precipitation (flooding) and temperature. Also, assessed the criticality and risk (magnitude of impact and the probability of occurrence). The study recognizes sensitivity and adaptive capacity are important, but are not easily calculated with time and data restraints.

61. Armstrong, A., C. Dorney, M. Flood, E. Garich, K, Krcma, M. Meyer, J. Ramsden, and E. Schecker-DaSilva. 2016. Alaska climate trend vulnerability study. Prepared by Parsons Brinckerhoff for FHWA. FHWA-WFL/TD-16-001, Vancouver, Washington.
https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/alaska/final_report/AlaskaAdaptationPilotReport.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Variable, primarily exposure/hazard mapping and risk
- Evaluation Scale(s): Spatial – variable, primarily regional; Infrastructure – variable, one example asset level
- Resource(s): Transportation assets
- Climate Factors/Hazards: Permafrost thaw, sea-level rise, changing wind and sea ice patterns, slope instability.
- Location: Alaska

- Notes: This document looks at three case studies from Alaska: the first examines impacts of permafrost on a highway, the second examines the risk of storm damage at an airport due to diminishing sea ice, and the last assessed landslides risk along Denali Park Road. All case studies used a 11-step process: 1) Describe the Site Context, 2) Describe the Existing/Proposed Facility, 3) Identify Climate Stressors That May Impact Infrastructure Components, 4) Decide on Climate Scenarios and Determine the Magnitude of Changes, 5) Assess Performance of the Existing/Proposed Facility, 6) Identify Adaptation Option(s), 7) Assess Performance of the Adaptation Option(s), 8) Conduct an Economic Analysis, 9) Evaluate Additional Decision-Making Considerations, 10) Select a Course of Action, and 11) Plan and Conduct Ongoing Activities. Step 4 focuses on the exposure and hazard mapping, where step 5 focuses on the sensitivity of the infrastructure.

62. ICF International. 2016. 2013-2015 Climate resilience pilot program: Outcomes, lessons learned, and recommendations. Prepared for FHWA. Report no. FHWA-HEP-16-079, Washington, D.C. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/final_report/fhwahep16079.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Variable, primarily: Vulnerability = exposure + sensitivity + adaptive capacity
- Evaluation Scale(s): Spatial – variable; Infrastructure – variable, primarily asset
- Resource(s): Transportation assets
- Climate Factors/Hazards: Variable
- Location: Variable
- Notes: This report summarizes the lessons learned from the previously discussed pilot projects, which assessed transportation vulnerability and evaluated options for improving resilience.

63. Massachusetts Department of Transportation (MassDOT). 2016. FHWA climate resilience pilot program: Massachusetts DOT. FHWA-HEP-16-073, Boston, Massachusetts. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/massdot/fhwahep16073.pdf

- Protocol: FHWA Climate Change Pilots, 2013-2015
- Specific Method: Exposure/hazard mapping
- Evaluation Scale(s): Spatial – site
- Resource(s): Tunnels, interchanges, bridges
- Climate Factors/Hazards: Sea-level rise, storm surge, and increase precipitation intensity
- Location: Massachusetts

- Notes: Calculated the vulnerability of the I-93 central artery/tunnel in Boston to sea-level rise and extreme storms. Ran the Advanced Circulation (ADCIRC) model, and decided exposure was a representative of vulnerability, rating all components as high sensitivity, and low adaptive capacity. Finally, developed adaptation strategies.

NPS/WCU Coastal Hazards & SLR VA Protocol (2015)

64. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, R.M. Scavo, M. Koslow, and B. Binns. 2015b. Big Cypress National Preserve Coastal Hazards & Climate Change Asset Vulnerability Assessment Protocol. NPS 176/154052. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272111

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method(s): Vulnerability = exposure + sensitivity
- Evaluation Scale: Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: BICY, Florida
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Big Cypress National Preserve (NPS/WCU).

65. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, R.M. Scavo, and M. Koslow. 2015c. Biscayne National Park Coastal Hazards & Climate Change Asset Vulnerability Assessment Protocol. NPS 169/154055. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272112

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: BISC, Florida
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Biscayne National Park (NPS/WCU).

66. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, and R.M. Scavo. 2015d Fort Sumter National Monument Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment Protocol. NPS 392/154056. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272120

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: FOSU, South Carolina
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Fort Sumter National Monument (NPS/WCU).

67. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, R.M. Scavo, M. Koslow, and B. Binns. 2015e. Gulf Islands National Seashore Coastal Hazards & Climate Change Asset Vulnerability Assessment Protocol. NPS 635/154054. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272121

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: GUIS, Florida, Mississippi
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Gulf Islands National Seashore (NPS/WCU).

68. Western Carolina University (WCU) and National Park Service (NPS). 2016. Coastal hazards and climate change asset vulnerability protocol: project description and methodology. NPS 999/132623. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2279632

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity.
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: Variable – coastal parks

- Notes: This protocol establishes a standard methodology and set of best practices for conducting vulnerability assessments in the built environment within the NPS. The assessments are currently focused on assets at risk to coastal hazards and sea-level rise within coastal parks. This protocol for the built environment (infrastructure, buildings, transportation, etc.) is indicator-based at the asset level, where vulnerability is calculated as a combination of exposure and sensitivity. The adaptive capacity of an asset is evaluated separately and is not included in the vulnerability score. Exposure indicators for this coastal hazard protocol include: flooding potential, extreme event flooding (e.g., storm surge), sea-level rise, shoreline change, and reported coastal hazards. Sensitivity indicators include: flood damage potential, storm resistance, asset condition, historical damage, and protective engineering. The primary data source for much of the sensitivity analysis is an asset-specific questionnaire.

69. Fatorić, S., and E. Seekamp. 2017. Assessing historical significance and use potential of buildings within historic districts: An overview of a measurement framework developed for climate adaptation planning. AG-832, NC State Extension, Raleigh, North Carolina. https://content.ces.ncsu.edu/assessing-historical-significance-and-use-potential-of-buildings

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity.
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: Cape Lookout, NC
- Notes: This study focused on climate change adaptation planning within Cape Lookout National Seashore. A standard framework was developed for measuring the relative significance of historic buildings, which included vulnerability (exposure and sensitivity). The vulnerability assessment methodology was developed separately by Western Carolina University (WCU). North Carolina State University researchers coupled the vulnerability assessment scores provided by WCU with historical significance

70. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo. 2017a. Acadia National Park Coastal Hazards & Climate Change Asset Vulnerability Assessment. NPS 123/154043. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272110

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method(s): Vulnerability = exposure + sensitivity
- Evaluation Scale: Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)

- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: ACAD, Maine
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Acadia National Park (NPS/WCU).

71. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo. 2017b. Cabrillo National Monument Coastal Hazards & Climate Change Asset Exposure Analysis & Case Study: Cliff Retreat Exposure. NPS 342/154057. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272113

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: CABR, California
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol of Cabrillo National Monument (NPS/WCU).

72. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo 2017c. Cape Lookout National Seashore Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment. NPS 623/154059. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272114

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method(s): Vulnerability = exposure + sensitivity
- Evaluation Scale: Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: CALO, North Carolina
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Cape Lookout National Seashore (NPS/WCU).

73. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo. 2017d. Canaveral National Seashore Coastal Hazards & Climate Change Asset Vulnerability Assessment. NPS 639/154060. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272115

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: CANA, Florida
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Canaveral National Seashore (NPS/WCU).

74. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo. 2017e. Colonial National Historical Park Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment. NPS 333/154061. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272116

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method(s): Vulnerability = exposure + sensitivity
- Evaluation Scale: Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: COLO, Virginia
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Colonial National Historical Park (NPS/WCU).

75. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo. 2017f. George Washington Memorial Parkway & Theodore Roosevelt Island Coastal Hazards & Climate Change Asset Vulnerability Assessment. NPS 800/154053. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272122

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: GWMP, Washington, D.C., Maryland, Virginia; THIS, Washington, D.C.

- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for George Washington Memorial Parkway and Theodore Roosevelt Island (NPS/WCU).

76. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo. 2017g. Jean Lafitte National Historical Park and Preserve Coastal Hazards & Climate Change Asset Vulnerability Assessment. NPS 467/154051. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272124

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method(s): Vulnerability = exposure + sensitivity
- Evaluation Scale: Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: JELA, Louisiana
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Jean Lafitte National Historical Park and Preserve (NPS/WCU).

77. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo 2017h. National Mall and Memorial Parks Coastal Hazards & Climate Change Asset Vulnerability Assessment. NPS 802/154050. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272125

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: NAMA, Washington, D.C.
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for National Mall and Memorial Parks (NPS/WCU).

78. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo. 2017i. Olympic National Park Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment. NPS 149/154047. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272130

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity

- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: OLYM, Washington
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Olympic National Park (NPS/WCU).

79. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo. 2017j. Padre Island National Seashore Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment. NPS 613/154046. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272131

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: PAIS, Texas
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Padre Island National Seashore (NPS/WCU).

80. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo. 2017k. Sitka National Historical Park Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment & Tsunami Vulnerability Case Study. NPS 314/154045. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272132

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method(s): Vulnerability = exposure + sensitivity
- Evaluation Scale: Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: SITK, Alaska
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Sitka National Historical Park (NPS/WCU).

81. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo. 2017l. War in the Pacific National Historical Park Coastal Hazards & Climate Change Asset Vulnerability Assessment. NPS 474/154044. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272133

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: WAPA, Guam
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for War in the Pacific National Historical Park (NPS/WCU).

82. Peek, K.M., B.R. Tormey, H.L. Thompson, R.S. Young, S. Norton, R.M. Scavo, and M. Koslow. 2018. Outer Banks (OBX) Group: Cape Hatteras National Seashore, Wright Brothers National Memorial, & Fort Raleigh National Historic Site Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment. NPS 910/154048. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272127

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: CAHA, WRBR, FORA, North Carolina
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Outer Banks Group (CAHA, WRBR, FORA) (NPS/WCU).

83. Tormey, B.R., K.M. Peek, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo. 2018a. Fire Island National Seashore Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment. NPS 615/154058. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272117

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)

- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: FIIS, New York
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for Fire Island National Seashore (NPS/WCU).

84. Tormey, B.R., K.M. Peek, H.L. Thompson, R.S. Young, S. Norton, J. McNamee, and R.M. Scavo. 2018b. New Bedford Whaling National Historical Park & Roger Williams National Memorial Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment. NPS 962/154049. National Park Service, Washington, D.C. https://irma.nps.gov/DataStore/Reference/Profile/2272126

- Protocol: NPS/WCU Coastal Hazards & SLR VA Protocol
- Specific Method: Vulnerability = exposure + sensitivity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation (assets)
- Climate Factors/Hazards: Sea-level rise, flooding, storm surge, tsunamis, erosion, shoreline change, and historical flooding
- Location: NEBE & ROWI, Massachusetts
- Notes: Results for the Coastal Hazard and Sea-Level Rise Asset Vulnerability Assessment Protocol for New Bedford Whaling National Historical Park and Roger Williams National Memorial (NPS/WCU).

NPS/URI Integrated Coastal Climate Change Vulnerability (2017-2019)

85. Ricci, G., D. Robadue, Jr., P. Rubinoff, A. Casey, and A. L. Babson. 2019a. Integrated coastal climate change vulnerability assessment: Colonial National Historical Park. Natural Resource Report NPS/COLO/NRR—2019/1945. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2264709

- Protocol: NPS/URI Integrated Coastal Climate Change Vulnerability
- Specific Method(s): Vulnerability = exposure + sensitivity. Adaptive capacity assessed separately.
- Evaluation Scale: Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation
- Climate Factors/Hazards: Sea-level rise, storm surge, flooding, shoreline change, and historical flooding
- Location: Virginia, Maryland (COLO)
- Notes: This project focused on the climate change vulnerability of coastal national parks, and include an analysis of natural resources, cultural resources, and infrastructure. The methodology is indicator-based, where vulnerability is calculated as a combination of exposure and sensitivity. For infrastructure, the assessment was conducted at the asset-level

using methodology developed separately by NPS/WCU (see NPS/WCU Coastal Hazards & SLR VA Protocol).

86. Ricci, G., D. Robadue, Jr., P. Rubinoff, A. Casey, and A. L. Babson. 2019b. Method for integrated coastal climate change vulnerability assessment. Natural Resource Report NPS/NER/NRR—2019/1933. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2263494

- Protocol: NPS/URI Integrated Coastal Climate Change Vulnerability
- Specific Method: Vulnerability = exposure + sensitivity. Adaptive capacity assessed separately.
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation
- Climate Factors/Hazards: Sea-level rise, storm surge, flooding, shoreline change, and historical flooding
- Location: Variable
- Notes: This project focused on the climate change vulnerability of coastal national parks, and include an analysis of natural resources, cultural resources, and infrastructure. The methodology is indicator-based, where vulnerability is calculated as a combination of exposure and sensitivity. For infrastructure, the assessment was conducted at the asset-level using methodology developed separately by NPS/WCU (see NPS/WCU Coastal Hazards & SLR VA Protocol)

FHWA Frameworks and Summaries

87. Choate, A., B. Dix, B. Rodehorst, A. Wong, W. Jaglom, J. Keller, J. Lennon, C. Dorney, R. Kuchibhotla, J. Mallela, S. Sadasivam, and S. Douglass. 2017. Synthesis of approaches for addressing resilience in project development. Prepared by ICF International, WSP USA, and South Coast Engineers for FHWA. FHWA-HEP-17-082, Fairhope, Alabama. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/synthesis/fhwahep17082.pdf

- Protocol: FHWA Frameworks and Summaries
- Specific Method: Resilience; no specific formula for vulnerability, mentions exposure and sensitivity
- Evaluation Scale(s): Spatial – variable; Infrastructure – primarily asset
- Resource(s): Transportation assets/infrastructure
- Climate Factors/Hazards: Variable
- Location: Variable

- Notes: This report is a summary and lessons learned related to the FHWA Climate Change Pilot Studies (2013-2015), which address climate change/extreme weather at the transportation asset level.

88. Filosa, G., A. Plovnick, L. Stahl, R. Miller, and D. Pickrell. 2018. Vulnerability assessment and adaptation framework, third edition. FHWA-HEP-18-020. U.S. DOT Volpe Center and FHWA, Cambridge, Massachusetts. https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/climate_adaptation.pdf

- Protocol: FHWA Frameworks and Summaries
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity; Risk/vulnerability = criticality X potential impact
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation
- Climate Factors/Hazards: Variable
- Location: Variable
- Notes: This document is the third edition of the vulnerability assessment framework for infrastructure, and utilizes an indicator-based VA. The framework also includes measuring the risk of the climate impacts, which includes measuring both the probability and severity/consequence of the impact. The revised protocol suggests three routes for completing a vulnerability assessment: 1) stakeholder input, 2) indicator-based desk review, and 3) engineering informed assessments for specific assets. Finally, the protocol suggests identifying, analyzing, and prioritizing adaptation options/strategies, including an economic analysis.

Individual Studies

89. City of Boston. 2016. Climate Ready Boston Final Report. Boston, MA. https://www.adaptationclearinghouse.org/resources/climate-ready-boston-final-report-2016.html

- Protocol: n/a
- Specific Method: Exposure
- Evaluation Scale(s): Spatial – asset site and city, community; Infrastructure – asset
- Resource(s): Infrastructure and transportation
- Climate Factors/Hazards: Extreme heat, stormwater flooding, coastal and riverine flooding
- Location: Boston, Massachusetts
- Notes: This study describes an exposure and consequence analysis of building and critical infrastructure. Exposure was calculated by comparing the location of infrastructure with stormwater, coastal, and riverine flood hazard data. Consequence was calculated using depth damage functions compared to expected percent loss and displacement time. Cost of

displacement and physical damage was calculated based on percent loss and displacement time.

90. City of Carlsbad. 2017. City of Carlsbad sea-level rise vulnerability assessment. https://carlsbadca.prod.govaccess.org/home/showdocument?id=5795

- Protocol: n/a
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity; risk assessment (qualitative)
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Critical infrastructure and transportation
- Climate Factors/Hazards: Sea-level rise and coastal hazards
- Location: Carlsbad, California
- Notes: The study uses the indicator-based methodology where vulnerability is a combination of exposure, sensitivity, and adaptive capacity. A numerical rating system was used to develop an overall vulnerability rating (low, moderate, high) for each asset category at the 2050 and 2100 time horizons. Study explains that the built environment has a low adaptive capacity.

91. ICF International. 2017. Safeguarding FWS infrastructure from extreme weather and other hazards. Prepared by ICF International, subcontractor to Vanasse Hangen Brustlin (VHB), under FHWA contract no. DTFH71-13-D-00001, Washington, D.C. https://onlinepubs.trb.org/onlinepubs/Conferences/2017/Parks/BhatC.pdf

- Protocol: n/a
- Specific Method: Vulnerability = exposure + sensitivity + adaptive capacity
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Infrastructure and transportation
- Climate Factors/Hazards: Sea-level rise, inland flooding, extreme heat, wildfire, and landslides
- Location: Pacific Region of U.S.
- Notes: This document describes the goals, outcomes, and lessons learned from work related to climate change vulnerability for FWS infrastructure in the Pacific Region. This project uses an indicator-based VA methodology where vulnerability is a combination of exposure, sensitivity, and adaptive capacity. Both sensitivity and adaptive capacity metrics were based on data already existing within the FWS infrastructure database. Scores were assigned to indicators yielding an asset vulnerability score for five different hazards: sea-level rise, inland flooding, extreme heat, wildfire, and landslides. Exposure scoring used a variety of mapped data sources. Sensitivity scores (except for landslides) were based on data mined

from the FWS asset management database (SAMMS). Adaptive capacity scores were also based on data mined from SAMMS.

92. City of Everett. 2018. City of Everett hazard inventory and vulnerability analysis 2018. Prepared by City of Everett Office of Emergency Management and City of Everett Utility Mapping, Mapping and Data Analysis, and the University of Washington. https://everettwa.gov/DocumentCenter/View/13997/EverettHIVA_2018

- Protocol: n/a
- Specific Method: Exposure, vulnerability (sensitivity measures), risk (intersection of hazard, exposure, and vulnerability)
- Evaluation Scale(s): Spatial – site; Infrastructure – asset
- Resource(s): Critical infrastructure
- Climate Factors/Hazards: Earthquakes, severe storms, pandemics, climate change, fire, flooding, hazardous materials, landslides, tsunami and seiche, and volcanic eruptions
- Location: Everett, Washington
- Notes: This study describes the hazards and vulnerabilities within the town of Everett, Washington. The scope of the study includes identifying probable hazards to which the city may be exposed, assessing the impacts, determining exposure, identifying assets, and analyzing vulnerability. Finally, the study presents potential mitigation measures and associated preparedness, response, and recovery. Exposure was evaluated by overlying hazards with an inventory of potentially vulnerable structures, facilities, and systems; vulnerability (sensitivity) was determined by interpreting the potential weakness/problems associated with any particular resources (e.g., built to code vs. not built to code).

Appendix E: Natural Resources Vulnerability Assessment Citations

Explicit Natural Resource Vulnerability Assessments

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Comer PJ et al. 2012. Climate change vulnerability and adaptation strategies for natural communities: Piloting methods in the Mojave and Sonoran deserts. Technical. NatureServe, Arlington, VA.

Fisichelli NA. 2013. Climate change trends for the State of the Park report, Valley Forge National Historical Park, Pennsylvania. National Park Service Climate Change Response Program.

Fisichelli NA, Janowiak M, Jones K, Peters M. 2014. Forest vulnerability to climate change and tree pests at Marsh-Billings-Rockefeller National Historical Park. Page 68. Natural Resource Report NPS/MABI/NRR 2014/828. National Park Service, Fort Collins, Colorado.

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Gonzalez P. 2014b. Climate Change Summary, Wupatki National Monument, Arizona. Page 9. Natural Resource Stewardship and Science, National Park Service, Washington, D.C.

Gonzalez P. 2014c. Climate change trends and vulnerabilities in Acadia National Park, Maine. National Park Service, Washington, D.C.

Gonzalez P. 2014d. Twentieth and twenty-first century climate trends at Mesa Verde National Park and Yucca House National Monument, Colorado. Page 9. Natural Resource Stewardship and Science, National Park Service, Washington, D.C.

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Halofsky JE, Peterson DL, O'Halloran KA, Hoffman CH. 2011. Adapting to climate change at Olympic National Forest and Olympic National Park. Page 144. General Technical PNW-GTR-844. U.S. Department of Agriculture, Forest Service, Portland, Oregon. Available from https://www.fs.fed.us/pnw/pubs/pnw_gtr844.pdf (accessed March 18, 2022).

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Appendix F: Evaluation Rubric, National Park Climate Change Vulnerability Assessments for Cultural Resources

A. Park/Unit: As it is written on the report title.

B. Year: Year released or year of latest draft.

C. Lead Author: Last name of lead author.

D. Report title: First full phrase of the title.

E. Scale: Dropdown. Options: ‘One unit’, ‘multiple units’, ‘region-wide’, ‘nation-wide’.

F. Scope: Dropdown. Options: ‘Integrated with Natural or Other Resources’, ‘Cultural Resources Only.’

G. Type of Cultural Resource: Options: Archeology, cultural landscape, buildings and structures, ethnographic resources, museum collections, multiple.

H. Hazards/stressors. Options: coastal erosion, inland erosion, fire, permafrost melting, invasive species, multiple, other.

L. Defining Exposure: Options: ‘Term not used’, ‘Term used but not defined,’ and if it’s used, verbatim citation of the definition.

M. Measuring Exposure: Options: ‘Qualitative,’ ‘Quantitative,’ ‘Quantitative and Qualitative’.

N. Describing Exposure: Narrative.

O. Defining Sensitivity: Options: ‘Term not used’, ‘Term used but not defined,’ and if it’s used, verbatim citation of the definition.

P. Measuring Sensitivity: Options: ‘Qualitative,’ ‘Quantitative,’ ‘Quantitative and Qualitative’.

Q. Describing Sensitivity: Narrative.

R. Exposure and Sensitivity: Narrative. How assessment of sensitivity reflects difficulty of addressing exposure?

S. Measuring Vulnerability A: Options: Qualitative, Quantitative, Quantitative and Qualitative, N/A.

T. Describing Vulnerability: Narrative: describes means of measuring sensitivity.

U. Adaptive Capacity: Describes how assessment of vulnerability includes concept of adaptive capacity. N/A option.

V. Transferability: Options: ‘Highly transferable’, ‘Designed to be transferable but needs additional resources’; ‘not explicitly designed to be transferable.’

W. Genesis: Narrative. Describes how each project got its start, if applicable.

X. Project Lead affiliation: Options: ‘NPS Administrative’, ‘NPS Resource Specialist’, and ‘Academic’.

Y. Recommendations: Options: no management recommendations, management recommendations in simple list, management recommendations prioritized in bands/tiers – no next steps, management recommendations prioritized in bands/tiers.

Z. Outcomes narrative: Options: 'Successful', 'Largely successful,' 'Partly successful.' Also, text: Additional details regarding the outcome of the effort.

AA. Report Recommendations: Text. Narrative of recommendations in the report.

AB. Comments: Any additional comments.

Appendix G: National Park Climate Change Vulnerability Assessments for Cultural Resources: Summary of Resource- and Unit-Specific Recommendations from Reports.

Note: Those not mentioned did not include specific recommendations. Recommendations for Assessment Methods are in Conclusion of Report.)

Peek et al. 2012

- Georeference assets
- Define the relation of assets to hazard zones
- Consistently update all data in FMSS

Wilson 2014

- Maintain access to sufficient qualified staff/expertise to conduct assessments.
- Educate staff who have experienced climate related emergencies on preparedness and mind-set
- Scope technological solutions to offset or mitigate threats

Newland 2013

- Develop and implement inventory and sampling strategies based on sensitivity
- Conduct cyclical monitoring of resource condition
- Create Memoranda of Understanding for treatments

Fatorić and Seekamp 2016, 2017

- Relocate historic structure
- Install protective fencing
- Stabilize for historic integrity
- Stabilize for adaptability
- Document new condition
- Interpret the change

Anderson 2016

- Georeference assets
- Develop and implement inventory and sampling strategies based on sensitivity
- Implement coastal erosion monitoring program
- Work with local community to scope options
- Develop educational and interpretive materials

- Conduct oral history interviews for historical baselines
- Document local collections of cultural resources
- Implement appropriate data-sharing with local stakeholders

Allen 2017

- Use new categories of extant data (e.g., insurance maps)
- Strategic mitigation/offsetting of impacts (e.g., beach nourishment)
- Direct and repeated engagement with local communities

Melnick et al. 2016a, 2017

- Collect high precision data and create maps
- Monitor cyclically for impacts
- Make use of specialized expertise (e.g., orchardist)
- Build resilience of living elements (of cultural landscapes)
- Form conservation partnerships with local and Native groups

Ensure that cultural resources and other SMEs are consistently included in effort

NPS 999/181593, June 2022

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525