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Vulnerability Assessments and Resilience Planning at Federal Sites

Synthesis of Project Results

February 2016

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Abstract

U.S. government agencies are now directed to assess the vulnerability of their operations and facilities to climate change and to develop adaptation plans to increase their resilience. Specific guidance on methods is still evolving based on the many different available frameworks. This technical paper synthesizes lessons and insights from a series of research case studies conducted by the investigators at facilities of the U.S. Departments of Energy and Defense. The paper provides a framework of steps for climate vulnerability assessments at Federal facilities and elaborates on three sets of methods required for assessments, regardless of the detailed framework used. In a concluding section, the paper suggests a roadmap to further develop methods to support agencies in preparing for climate change.

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1.0 Introduction

1.1 The Need for Climate Vulnerability Screening and Assessment

The U.S. Department of Energy (DOE), the Department of Defense (DOD), and other government agencies are increasingly concerned about potential impacts of climate change on their infrastructure, operations, and mission. Some climate change impacts are already being observed, and in the future, their occurrence is certain to increase as climate change itself accelerates. The degree to which damage to critical infrastructure and government functions can be avoided depends on developing reliable information about potential impacts and using this information to adapt existing facilities and locate new ones out of harm's way.

U.S. government agencies are now directed to assess the vulnerability of their operations and facilities to climate change to anticipate and prepare for climate change impacts. Two Executive Orders (E.O. 13653, 2013; and E.O. 13693, 2015) focus on the need to plan for adaptation, and the operating and sustainability plans of most agencies include climate change considerations. (See Appendix A for a list of relevant DOE Orders and DOD regulations.) Consequently, agencies are experimenting with different approaches to meet directives from the Executive Branch and their agency leadership.

The task confronting agencies is enormous. For example, DOD alone owns and/or operates approximately 4,800 sites worldwide (about 24.9 million acres), of which some 294 are active major installations (DOD, 2015). Also, DOE is the fourth largest land manager, executing its mission at 50 major sites on 2.4 million acres of land (DOE, 2015). Needed at this time is an efficient and systematic process to select a manageable set of priority sites and infrastructure systems that are most important and vulnerable, assess vulnerabilities of this subset, and support detailed adaptation planning where essential. Conducting thorough vulnerability assessments of specific sites will only be necessary where agency missions and operations are likely to be materially affected by changes in climate.

1.2 Overview and Purpose of This Technical Paper

This paper provides a synthesis of concepts, approaches, and methods used in a series of climate vulnerability assessment case studies conducted at DOD and DOE installations. This report is a revised version of a report published in August 2015 that was used to elicit comments and feedback from program managers responsible for implementing vulnerability assessments. The report has been updated to reflect these comments and supersedes the previous version.

The paper describes a three-tiered approach to screen installations for climate vulnerability to prioritize the need for assessments (tier 1); conduct assessments at select sites (tier 2); and develop adaptation options to increase resilience of vulnerable systems and activities (tier 3). The paper focuses on *facility-level* vulnerability assessments, summarizing a framework and process for assessing vulnerabilities at sites that were prioritized because of their importance to mission, ongoing damages from current conditions, or other factors such as willingness of site personnel to participate in the research. The paper also discusses requirements and options for a typology of three categories of methods required for any climate vulnerability assessment, regardless of the detailed framework used: (1) engaging stakeholders and collecting data, (2) providing climate information, and (3) modeling potential impacts. This approach could increase efficiency while also allowing for detailed analysis where needed.

Drawing from the case study findings, we discuss conceptual and framing topics, including whether climate vulnerability assessments are needed, what the case study results suggest about basic concepts used to structure information collection, the overall three-tiered framework, and the issue of cross-site screening to identify where installation climate vulnerability assessments are warranted. The paper concludes with observations about the need for a more systematic development and evaluation of methods and increased communication across agencies conducting assessments to share experience and promote learning. Climate vulnerability assessments and adaptation planning will be iterative, but taking advantage of one of the benefits of iterative processes—learning—can best occur if results are developed and compared in a systematic fashion.

1.3 Background: What's in a Definition? Alternative Framings of "Climate Vulnerability"

The problem of assessing vulnerabilities is compounded by alternative definitions of key concepts and terms. This is not just an academic issue. It fundamentally drives information collection and analysis. We reviewed the implications of different definitions for assessment structure, and also considered the relevance of other approaches including risk assessment and resilience analysis from engineering, ecological, cyber, critical infrastructure, disaster risk management, and other perspectives. The focus of this technical paper is not on comparing and reconciling differences in definitions or approaches but rather on developing a practical and understandable approach grounded in the literature on climate change vulnerability that has the potential to work at Federal sites.

At the beginning of our case studies, we adopted the definition of "vulnerability" that is widely used in climate adaptation studies: susceptibility to damage from current or future climate variability and extremes. This definition explains vulnerability as a function of

- *exposure* - the climate phenomena to which the facility is subjected
- *sensitivity* - the extent to which important characteristics are disrupted or changed by climate exposure
- *adaptive capacity* - the extent to which adjustments are possible that reduce negative impacts or make them easier to recover from

As we conducted our case studies and received feedback from the participants, we concluded that this definition was potentially confusing, particularly the emphasis on climatic variability and extremes. It had the unintended effect of giving primary emphasis to climate conditions, a perception that was counterproductive given that site conditions were at least as important as climate factors in understanding vulnerabilities and the significance of climate change for mission attainment. Therefore, we revised our working definition and the description of the approach.

As illustrated in Figure 1, we adopted an approach that defines climate vulnerability solely as a function of the characteristics of a facility that determine its susceptibility to damage, thus emphasizing sensitivity and adaptive capacity as defined above. Exposure is still crucial but now distinct from vulnerability and depends on the evolution of the climate system and related environmental conditions. This formulation more clearly distinguishes the characteristics of facilities from the exposures that exploit those vulnerabilities to produce impacts.

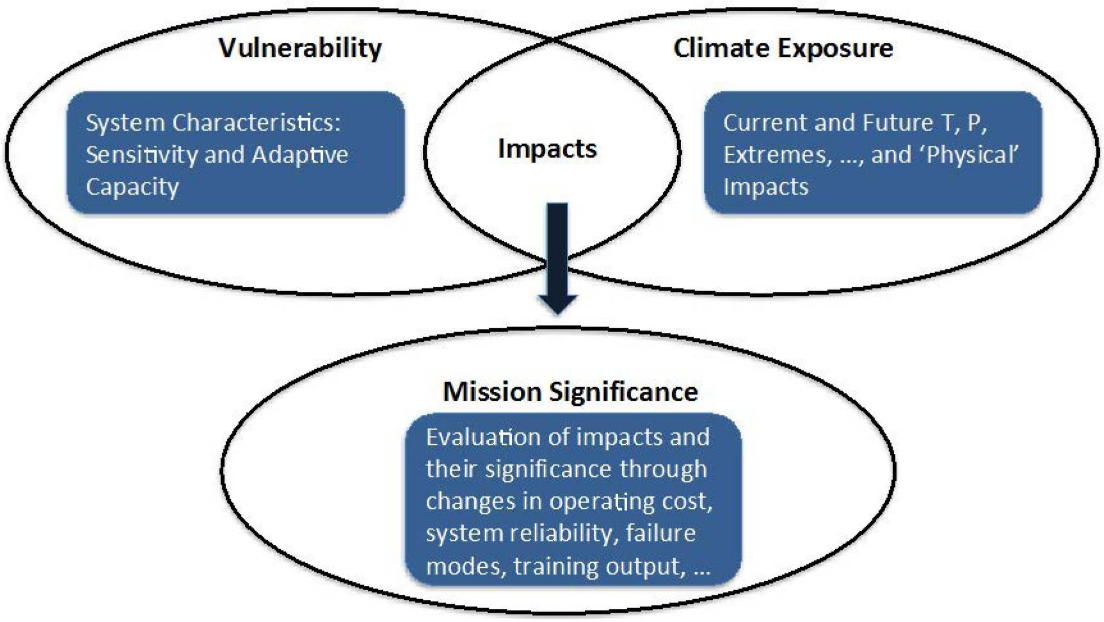

Figure 1. Climate Vulnerability Defined as a Pre-Existing Condition Based on Characteristics of a Facility or System (T=temperature; P=precipitation). Climate exposures exploit vulnerabilities to produce impacts and affect mission attainment.

"Impacts" result when climate vulnerability and exposure collide – the resulting damages, injury, or harm (for example, the physical damage to a building, bridge, or training area). In our experience with the sites, participants noted that the existence of potential impacts resulting from climate vulnerability and exposure was not sufficient to reach conclusions about risks to mission attainment and to justify changes in procedure, policy, or infrastructure. Thus, we explicitly added a step for assessing "significance" to our conceptual approach. Climate vulnerability assessments need to identify not only the physical damage or impacts, but how these could affect outcomes that are important to achieving missions within budget and acceptable tolerance for failure. Stakeholder input is crucial to this final step.

The alterations from our original approach are important for framing and analyzing climate vulnerability in ways that are more relevant to stakeholders. This new framework clarifies several important aspects of the problem, as well as the processes and methods needed to address it:

- *Prioritizes information collection on site characteristics*: Considering climate vulnerability as a pre-existing condition or property of the facility or infrastructure being assessed emphasizes the importance of systematically gathering and analyzing information about the facilities – information about future climate conditions is not sufficient in itself, as some participants were inclined to think.
- *Focuses climate analysis*: Clarifying that vulnerability arises from facility characteristics highlights that developing climate information need not be the first step in climate vulnerability assessment. In fact, first identifying which aspects of a system are vulnerable – and why – helps develop priorities for climate analysis by identifying which specific climate variables or processes are most important.
- *Can empower site personnel*: This conceptual approach emphasizes that impacts and their consequences more clearly depend on the decisions and stewardship of facility operators and managers, not only on climate factors they cannot control.

- *Clarifies the roles of impact modeling and assessment of impact consequences*: Finally, distinguishing "physical impacts" (for example, damage to structures) from their ultimate "significance" for mission attainment (for example, service interruptions, increased costs, lost training capacity) shows the importance of stakeholder engagement methods that enable facility operators and managers to grapple with how specific impacts could affect their objectives and missions, and what they might do to recover from these damages or increase their resilience through adaptation. It defines a clear role for activities such as impacts modeling, but also clarifies their limits. We will return to this topic of methodological resources and gaps in the concluding section of this technical paper.

A final observation that reflects input from several participants in the case studies is that regardless of what detailed framing of climate vulnerability is used, it is important to look for potential benefits in addition to vulnerabilities, and to plan to exploit these as a component of increasing resilience. Modeling of infrastructure systems and natural resources used for training or other activities can reveal increased productivity or reduced costs as well as potential impacts. In this paper, we do not consider whether to reframe the challenge of preparing for climate change in terms of "resilience", which could incentivize stakeholders to participate and provide information by aligning climate preparedness with other sustainability objectives. Other approaches to climate vulnerability assessment include risk assessment and analysis of resilience from engineering, ecological, cyber, critical infrastructure, disaster risk management, and other perspectives (for example, IPCC 2012 seeks to integrate climate vulnerability and disaster risk management approaches; Linkov et al., 2014, argue for integration of risk analysis into resilience planning; Larkin et al., 2015 review integration of risk and resilience science within Federal agencies; Bowyer et al., 2015 review methods for developing adaptation strategies that frame the issue as managing climate risk). As climate vulnerability assessment, adaptation planning, and promotion of climate resilience are incorporated into existing areas of practice such as civil engineering and ecosystems management, it will be important to at least clarify, if not resolve, different definitions ascribed to such terms as "threat," "vulnerability," "consequence," "exposure," and "resilience."

1.4 Basis of this Paper: Vulnerability Assessment Case Studies

Our research into climate vulnerability assessment methods for Federal sites is based on a limited number of case studies. The work was sponsored by the DOD Strategic Program for Environmental Research and Development (SERDP) and the DOE Sustainability Performance Office (SPO) through two related research projects. These projects involved experimenting with quantitative metrics for screening as well as the case studies themselves. In conducting the site-level vulnerability assessments, we explored different approaches and methods for framing the problem, collecting information, analyzing climate exposure, modeling impacts, and assessing significance of potential impacts for future operations and mission attainment.

Most of the work was conducted at sites in the mid-Atlantic region of the United States. A climate vulnerability assessment case study was conducted at DOE's Thomas Jefferson National Laboratory, located in Newport News, VA. The SERDP research projects were also conducted at three installations in the mid-Atlantic region. In addition, a related climate vulnerability assessment and resilience planning project that made use of different sources of climate information was conducted at Pacific Northwest National Laboratory, located in Richland, WA. Finally, beyond conducting site level assessments, we experimented with different approaches to conduct initial high-level screening to set priorities for site assessments using survey and enterprise-level data sets. Together, these case studies provided a range of facility sizes, coastal and inland locations, types of infrastructure, potential climate stresses, and decision processes.

2.0 Screening and Assessment in a Multi-Tiered Process

Federal agencies manage a large number of complex and unique facilities in diverse geographical settings. A multi-tiered approach for climate vulnerability assessment is required to prioritize the assessments and reduce costs while still allowing for detailed assessment where needed. We suggest a tiered approach that has three levels of analysis and is depicted in Figure 2. The first tier includes a screening of all agency sites to set priorities. The middle tier focuses more detailed assessments at sites identified as most vulnerable. The third tier comprises analysis of adaptation options. This tiered process is designed to take advantage of existing data and expertise of site managers, and to supplement this expertise with focused information on vulnerability, exposures, impacts, and their consequences. We briefly describe the objectives and functions of each tier.

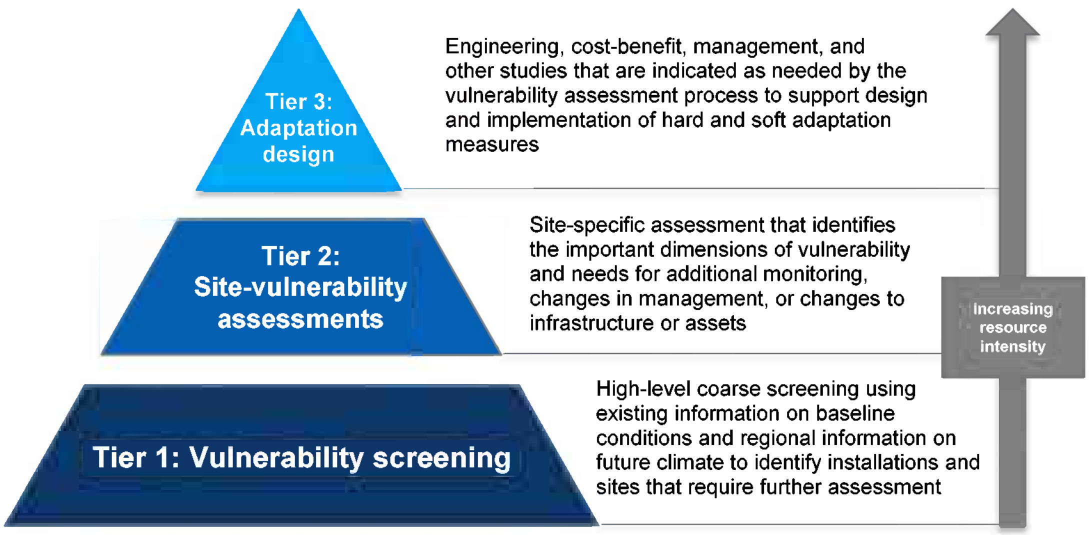

Figure 2. Tiered, Multi-Criteria Framework to Climate Vulnerability Assessment

1. **Vulnerability screening**: department- or program-wide comparative analysis of sites is undertaken to identify the most vulnerable sites that merit additional vulnerability assessment. Robust prioritization is based on indicators of vulnerability that are comparable across sites, yet take into account each site's baseline conditions, impacts of exposure, and effect on mission and operations. Available approaches combine site questionnaires and development of indicators that use existing data collected for other purposes. Ranking must be done efficiently, using existing data to the greatest extent possible; although at this time, it is likely that additional information will need to be provided by site personnel. A climate vulnerability screening will determine whether a site-vulnerability assessment is warranted or not. For many sites, this level of analysis may be all that is necessary.

2. **Site-vulnerability assessments**: for installations and infrastructure prioritized through the screening process, potential vulnerabilities are analyzed across the site or system. The objective of this assessment level is to clarify whether potential vulnerabilities need to be addressed through additional monitoring, alterations in management practices, or structural changes. This step uses stakeholder engagement, several approaches for characterizing past and future exposure, and methods for modeling potential impacts (for example, infrastructure models, geographical information systems, network models,

and other techniques). Among the issues considered are past and ongoing impacts of climate extremes (including the thresholds at which such impacts occur), upcoming expansion/investment decisions, potential impacts of changes in exposure on key sectors or systems, the potential for network or cascading failures, review of adaptation options that have already been implemented, and identification of next steps based on assessment of mission/operational significance. This tier uses:

- Stakeholder engagement to bound the assessment, gather information about baseline conditions, and identify the need for interactions with communities adjacent or important to the site.
- Several approaches for characterizing past and future climate exposure.
- Methods for modeling potential impacts (for example, infrastructure models, geographical information systems, and network models).
- Additional stakeholder engagement to assess consequences and options for adaptive management.

While more thorough and accurate than the tier 1 screening process, this tier of assessment would not typically include detailed analysis of structural adaptations such as revision of design criteria and re-engineering of infrastructure systems. The expert knowledge of site personnel and information from site records and data (including planning documents) are a crucial input, which places a premium on methods for data collection, as needed information can be scattered across multiple offices and/or departments and be incomplete and incompatible. Conclusions that can result from this level of analysis are to improve targeted data collection; monitor and periodically re-assess conditions, performance, damages, and other factors; undertake more detailed analysis of a system, sector, network, or practice; and take action to address specific risks of sufficient likelihood and consequence. In many cases, exactly how to act will require an adaptation design process, the third tier of assessment.

3. **Adaptation design and decision making**: if the site-vulnerability assessment identifies vulnerabilities that threaten mission-critical infrastructure or create hazards to safety and welfare, the third tier is required. The objective of this tier is to incorporate the risks resulting from vulnerability to climate change into ongoing planning and decision processes, for example, during design of already scheduled facility upgrades or expansion. The character of this analysis will vary depending on the nature of the system, location, or activity, as well as the type of potential adaptation being considered. It could include detailed analysis of systems or networks, for example, using well-established engineering methods. The analysis may include examination of an external utility, transportation, or other systems on which the site depends, undertaken in conjunction with the broader community of which the facility is a part. In almost all cases, climate information will need to be customized to provide an accurate picture of potential future conditions, considering uncertainty bounds/ranges.

Major distinctions across these tiers are the objectives supported and the corresponding level of detail and quality of data required. Tier 1 and 2 each require information about baseline conditions and potential future exposure—simply completing an assessment of current conditions and impacts from ongoing climate variability will not be sufficient to identify whether assets are at risk and the next tier is needed. Tier 3 requires much more detailed information and analysis and can be seen either as a culmination of a climate vulnerability assessment or the initial phases of resilience enhancement.

This multi-tiered approach should leverage existing resources and data. If further developed and implemented iteratively as part of adaptive management, it would allow agencies to screen sites and/or sectors where investing more resources will yield the most benefit.

3.0 Tier 1: Climate Vulnerability Screening

The prospect of conducting a detailed vulnerability assessment that includes adaptation design and resilience at each and every facility, asset, or mission is not only daunting but also infeasible. The cost of such an effort would be considerable, while the benefits would vary significantly across sites. Instead, a screening process should first be implemented to identify those sites most likely to be negatively impacted by climate change and where resources should be dedicated to better understanding threats at these locations.

A good starting point for a screening analysis of future vulnerability is to identify and evaluate exposures to and impacts of current climate-related conditions – for example, the costs of preparing for and recovering from ongoing flooding associated with storms and high tides. Screening-level analysis needs to be efficient and rely on existing information and/or easily collected supplemental information for this purpose. Databases or interviews with site personnel can identify which exposures currently cause damages, and historical climate records (often of high quality) can be used to compile a record of the climate exposures for a particular facility or set of facilities. What has proved challenging in our case studies is obtaining even rudimentary information on climate-related damages. Existing management databases lack consistent coverage of damages attributed specifically to climate exposure, and often do not contain information on other factors affecting vulnerability. This means that it is currently not possible to develop mathematical damage functions because information on the costs of preparedness, impacts, and recovery are sparse.

As discussed in Section 2.0., in addition to information on potential exposure, information on site characteristics that result in vulnerabilities is needed for a screening analysis. Collecting information about site characteristics can be thought of as developing a vulnerability "baseline" that considers importance, condition, past damages, preparedness, and other factors. Developing a baseline does not constitute a complete screening, as the baseline must be evaluated against possible future climate and related environmental exposures to identify potential problems that warrant additional analysis.

Candidate methods for site screening include the following: department-level questionnaires, brief, structured interviews with on-site stakeholders, using publicly available historical exposure data, indicators that incorporate available information to facilitate ranking, and analyzing existing datasets that track characteristics of the site or facility. Each approach has strengths and weaknesses.

- Questionnaires are a useful technique in identifying past impacts, climate exposure thresholds at which damages occur, the effectiveness of current preparedness measures, and upcoming planning or decisions related to long-lived infrastructure that should consider potential climate change vulnerabilities. However, recall bias and staff turnover can limit effectiveness and accuracy and must be accounted for, especially related to identifying impacts that resulted from events that occurred in the more distant past.
- Publicly available exposure data is often of high quality and sufficient temporal scale to determine local exposures. However, without local context (that is, how exposure events interacted with the characteristics of the site to produce impacts), these data are of limited value. The data cannot explain why an exposure of comparable severity can cause very different levels of damage at similar sites or infrastructure systems (or on the same site at two different points in time).

- Indicators are increasingly popular as a tool to rank assets and thus allocate a limited budget efficiently. However, indicators are highly sensitive to the underlying assumptions of their construction, and the rankings they produce are not robust (see more detailed discussion, below).
- Institutional datasets, such as DOE's FIMS (Facilities Information Management System) and real property datasets used in several agencies, contain lists and descriptions of Department assets, which could be used in developing indicators. However, the desired variables are generally not tracked (impact costs, damage response functions, etc.), as they can be difficult or costly to measure.

Of these techniques, indicators are currently receiving a great deal of emphasis. Studies focused on composite indicators have cited approaches and guidance that could address some of these issues; of particular relevance are some of the approaches proposed by Balica et al. (2012), Cutter et al. (2010), Munda and Nardo (2005), and OECD (2008). Some of the cited "best practices" for indicators include the following:

- Considering the relevance of candidate variables to vulnerability and/or resilience, and evaluating the availability of high-quality and consistent data when selecting variables. Including the perspectives of a diverse group of stakeholders is useful for variable selection and gathering different points of view on the importance of the variables included in the indicator.
- Converting raw data values into comparable scales (using percentages, per capita and density functions, etc.) to avoid problems inherent when mixing measurement units that span a number of statistical units, ranges, and scales.
- Applying statistical tests to measure multicollinearity and consistency/reliability of composite indicators – For example, statistical reliability analyses can help ensure internal consistency and determine whether the sub-indicators/proxies are sufficient and adequate to describe vulnerability for the group of sites being studied.
- Introducing methods to transparently assign weights to components of composite indicators. Composite indicator scores can be highly sensitive to different weighting schemes. Assigned weights may not reflect the priorities of decision makers unless transparency is maintained and effort is taken to elicit their input (Esty et al., 2005). Sensitivity analysis to determine the impact of different weights for components on composite indicator scores is important.
- Identifying uncertainty – In particular, Balica et al. (2012) suggests that, while uncertainty is inherent in climate change vulnerability indicators, its use in risk management is useful for policy and decision makers in terms of prioritizing investments and formulating adaptation plans.

Given the challenges in obtaining consistent and good quality data on facility conditions affecting vulnerability, we are currently exploring methods that focus on using enterprise data systems (for example, facility condition indices maintained by many agencies) for vulnerability screening. Some of the information collected can provide insights on characteristics of infrastructure or assets that could indicate whether those assets are vulnerable or resilient to potential changes in climate. We are also investigating methods around exposure (for example, frequency and intensity of storms or floods). Historical data on exposures is readily available, and archives of climate model results can be mined for information on how exposure could change in the future under different emissions scenarios. If properly designed, an exposure-based indicator can be developed in an efficient process. Further work is occurring and required to validate the approach, especially considering the importance of facility-level thresholds and conditions that lead to significance differences in impacts.

4.0 Tier 2: Site-Vulnerability Assessments

To provide decision-relevant information, vulnerability assessments for Federal facilities need to include coordinated participatory and analytical processes that translate potential changes in climate into information about the consequences or significance of those changes for continued facility operations and mission attainment. Occupying the second tier in the overall process (tier 2 assessment in Figure 2, see Section 2), they should only be conducted at sites that are determined to be of high priority through initial screening (as discussed in section 3).

Installation vulnerability assessments typically produce information that is detailed enough to identify opportunities for changes in management or use of facility infrastructure (managed or natural) and the need for monitoring and analysis of conditions and performance of systems identified as vulnerable that have not yet experienced significant impacts. Vulnerability assessments do not typically provide detailed information on specifications or design of systems that would be resilient to future conditions, although they should identify the need for such planning. Thus, vulnerability assessments do not provide enough detailed information to support implementation of adaptation measures such as major changes in policy governing operations or structural changes in built or managed environmental systems (for example, introduction of a sea wall or modification to subsurface water conveyance systems). It is important to set participants' expectations so that they know that the vulnerability assessments will not themselves produce adaptation plans for specific systems that are identified to be at risk. Detailed engineering, hydrologic, and other studies will be required to produce designs for such adaptation measures.

Facility assessments use several methods, often including quantitative modeling of impacts, to connect climate change to outcomes of concern to managers and decision makers – everyday issues such as system reliability, damages to property, maintenance costs, and health and safety of employees. The assessments need to be flexible and nimble because initial results can lead in unexpected directions and require modeling or analysis capability that was not anticipated in the initial assessment design.

In this section of the paper, we present a concept for an assessment framework – a structured series of tasks joined in a logical process – that could provide a useful starting point for planning facility-level assessments at Federal sites. In doing so, we recognize that no single framework will be applicable to all or even a majority of cases confronting an agency; thus, we also present an overarching typology of methods needed to accomplish three objectives central to assessment, regardless of which detailed process is used.

In preparing the framework, we reviewed a wide range of theoretical and applied research on different methods and frameworks (Turner et al., 2003; Schröter et al., 2005; Füssel, 2007; Yohe and Leichenko, 2010; Glick et al., 2011; DOT, 2012; Csete et al., 2013; Buotte et al., 2014; and others). This technical paper does not contain a detailed literature review. However, Table 1 compares steps included in three foundational analyses in the literature. The approach we have developed merges facets of these and other approaches and combines them in ways that are relevant for assessments for DOD and DOE sites, particularly those where some of the most important vulnerabilities are related to fixed infrastructure assets, whether natural (ecosystems for training, lands managed for conservation and renewable energy production, etc.) or human-made (runways, electricity grids, buildings, etc.).

Table 1. Steps Involved in a Sampling of Vulnerability Assessments

Schröter et al. (2005)	Füssel (2007)	Csete et al. (2013)
(1) Collaboratively define the study area with stakeholders.	(1) Identify the system of analysis.	(1) Identify a supply typology, that is, sub-divide the sector of interest based on the weather and environmental dependence of the activity of interest.
(2) Get to know the place over time.	(2) Identify the attributes of concern.	(2) Identify exposure indicators, which should capably describe the spatially differentiated exposure of the locations of interest, in addition to the other components of exposure (socio-economic and environmental factors, climate factors, etc.).
(3) Generate hypothesis of system vulnerabilities (and to what).	(3) "Identify the hazard or potential event that might damage or affect the system of analysis and the particular attribute of concern."	(3) Identify sensitivity indicators, "a characteristical function of the affected system."
(4) Build causal model(s) of vulnerability.	(4) Identify the temporal reference, which can be either a point in time or period of interest.	(4) Identify indicators of adaptive capacity.
(5) Develop indicators for system vulnerabilities.	(5) "Identify the internal (i.e. from within the system of analysis), external (i.e. outside the system), and cross-scale vulnerability factors."	(5) Develop vulnerability maps. Vulnerability assessments of this type have tended to focus on larger areas of interest, predominantly regions.
(6) Operationalize the vulnerability model(s).	(6) "Identify the knowledge domain, which includes socio-economic, biophysical or integrated factors."	*Note: Vulnerability assessments of this type have tended to focus on larger areas of interest, predominantly regions.*
(7) Project future vulnerability.		
(8) Communicate vulnerability.		

4.1 Objectives and Participants

The framework for vulnerability assessments is designed to identify and analyze past and ongoing vulnerabilities to existing conditions, develop relevant climate information and impacts modeling, and analyze the operational and mission significance of potential future impacts to inform planning and management decisions. This is not a purely analytic task, although analysis is required if the information provided to decision makers is to be reliable. It requires tapping existing expertise, information, and knowledge at a range of governance levels, from the facilities themselves to the office or Service level to headquarters level. Assessments need to be thought of as carefully coordinated participatory and analytic processes, involving a range of facility stakeholders as well as subject matter experts.

In developing an assessment framework, we started from the assumption that climate vulnerability assessments could be designed to be useful to decisions in two distinct time frames. First were decisions taken within a decade or so that involved adjustments in policy and ongoing management as well as improvements to existing infrastructure. Second were decisions with long-term implications of a decade or more (build-out of new or renovated facilities, acquisition or decommissioning of bases, siting training activities and programs, logistical and other systems, etc.) that will be taken relatively soon, i.e., within the next decade, a typical planning horizon for such decisions.

An important observation is that it is most effective to incorporate climate information into ongoing planning and decision processes (GAO, 2013). This has led some stakeholders to conclude that vulnerability assessments are not needed and, in fact, could impede use of climate information in ongoing decision making. However, where sites are identified as potentially vulnerable through a screening process, facility-level assessments are needed because information about future climate conditions (temperature, precipitation, or even specific impacts-relevant climate variables such as a fire danger index) does not usually directly translate to decision-relevant variables without additional analysis. Table 2 illustrates this point, linking climate exposures, potential impacts, significance to management or decision making, and potential risk management options. Facility-vulnerability assessments need to incorporate this translation function, going from exposure through to risk management. In fact, it can be very useful if assessments are structured from the start to produce metrics or information on decision factors that are used in ongoing management and decision processes at a facility.

Table 2. The Need for Climate Vulnerability Assessments: Translating Exposure into Impact, Consequence, and Risk Management (Key: T=temperature; P=precipitation; RCW=Red Cockaded Woodpecker; CDD=cooling degree days; HDD=heating degree days; HVAC=heating, ventilation, and air conditioning)

Exposure	Impacts (Exposure + Vulnerability)	Significance for Mission and Operations	Risk Management (varies by governance level)
Increased fire risk	Fewer burn days; ecosystem condition; RCW	Costs; restrictions on training lands	Revise scheduling/budget; alter management; add training capacity at other sites
Ecosystem migration (change in flora/fauna ranges)	Threats to protected species; invasive species; movement of pests, disease vectors	Costs; mismatch of training requirements and lands; increase (or decrease) in restrictions	Alter management; redistribute training activities
Increase in days with extreme heat	Outdoor activity and training restrictions; energy system stress	Reduced training throughput; schedule interruptions	Alter training schedule; redistribute training activities
Change in surface wind speed	Flight training, parachute drop cancellations; controlled burn restrictions	Training throughput and readiness; changes in ecosystem maintenance	Alter training regimen; redistribute training activities; change burn patterns
Increase in storms (tropical, sub- and extra-tropical)	Training cancellations; ecosystem disturbance; infrastructure damage	Training, health and safety concerns; increased costs	Increase preparedness; alter maintenance contracts; recapitalize infrastructure; provide backup systems; delay/move training
Increased T	Increases in CDD; decreases in HDD; ecosystem disturbance	Inadequate HVAC system design; costs	Alter design standards; revise budget; revise conservation management protocols
Changes in P, runoff, T	Flooding, changes in water supply and storm water management; noncompliance with water quality requirements; infrastructure disruption (buildings, transport, etc.)	Use restrictions; supply system adaptation; altered suitability of locations for water-intensive activities; increased compliance costs	Budget for increased costs (cleanup, damage); alter management regimes; relocate water-intensive activities; change to surface/subsurface conveyance systems; adjust master planning, facilities criteria
Coastal flooding	Infrastructure disruption and damage	Costs; health and safety concerns; activity interruptions	Modify service contracts; increase budget; redesign infrastructure and facility; adjust master planning, facilities criteria

An important question is whether a facility-level assessment be carried out by an external team composed of subject matter experts or by an internal team of site staff. The choice is not categorical but rather a continuum of options with different implications for leadership, participation, and expertise. Research and our experience indicate that internally led processes are more successful in establishing ownership and empowering staff to act. But if an external team incorporates effective stakeholder engagement, externally led assessments can also lead to this desired outcome. A challenge for internally led assessments is identifying required expertise from among existing installation staff. Climate vulnerability assessments require expertise in engaging stakeholders, identifying and collecting data relevant to sensitivity and adaptive capacity, analyzing historical and potential future climate conditions, conducting impacts modeling for relevant infrastructure and natural systems, and leading charettes, scenarios, and other approaches to evaluate the mission significance of potential impacts. Based on our experience, internally led assessments require supplementing expertise of installation staff. The use of external assessment teams can be resource intensive and problematic if security issues exist. One option for agencies is to start an agency wide climate vulnerability assessment process by relying on external teams to build experience, evaluate methods and approaches, and develop opportunities to provide training and automated tools to its staff.

4.2 Framework for Facility-Level Vulnerability Assessments

The vulnerability assessment framework is pictured in Figure 3 and summarized as a set of five steps or tasks in Box 1.

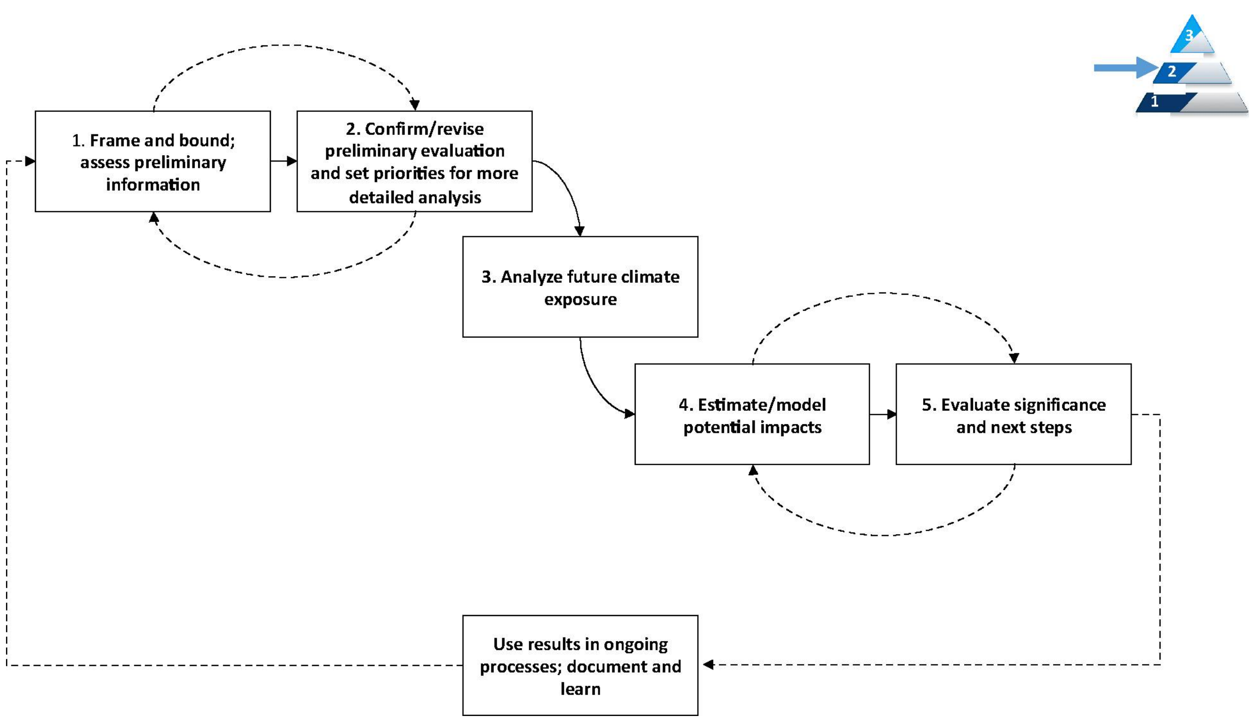

Figure 3. Iterative Vulnerability Assessment Process for Federal Sites

Box 1: Framework for Site Vulnerability Assessments

1. Frame the assessment: Establish purpose, set system boundaries, and collect/analyze preliminary information.
2. Confirm/revise preliminary evaluation and set priorities for more detailed analysis.
3. Analyze future climate exposure.
4. Estimate/model potential impacts.
5. Evaluate significance and agree on next steps.

Conduct assessments to support ongoing planning, budgeting, and decision-making processes. Document results to provide a baseline for future assessments.

We briefly discuss the purpose and nature of each step.

Step 1: Frame the Assessment: Establish Purpose, Set System Boundaries, and Collect/Analyze Preliminary Information

Framing the assessment is an iterative process that involves making decisions about who will use the results and how, determining which infrastructure or operations will be evaluated, getting a sense of the existing information base, and framing initial questions and ideas about vulnerability for further exploration with site personnel. An assessment can only be useful if those who are responsible for it articulate how they will use it. With a clear idea of both audience and purpose, the assessment team can produce implementable information and analysis. An assessment may be desired by site personnel, for example, who intend to use the information in an upcoming master planning or system-design process. This would mean that, among other outputs, the assessment would need to produce information about potential damages for planned infrastructure or load requirements for a system. Or, as was the case in the assessments we conducted, the assessment may be required by the department, office, or program responsible for providing oversight of the site. In this case, site personnel might be interested in information about overall operating costs or the ability of a facility to meet training or other targets under different future scenarios. It will likely be the case for any particular assessment that multiple governance levels will be involved.

Framing also establishes the authority under which the assessment will be conducted. Conducting the assessment will require cooperation of facility operators and managers and obtaining access to information about mission dependence, current conditions, budget, and other matters that are sensitive. Without direction from a recognized authority, site personnel may not feel empowered to provide the needed information. A clear agreement on what will be required going into an assessment will enable all engaged parties to prepare and set aside the necessary resources (including staff time) for participation.

Bounding the system is crucial in assessing the vulnerability of a site because of the complexity and large number of subsystems that can support operations. As a result, some component infrastructure or natural resource systems may need to be excluded from an initial vulnerability assessment. This step helps establish agreed priorities, especially if funds or time available for needed modeling and analysis are limited. Bounding the system is also important because of the dependencies that most Federal sites have on their surrounding communities and environment. These dependencies include provision of required inputs such as electricity, water, sewage treatment, and other basic utilities; agreements regarding operations and "encroachments" that influence operations at the installation and that could require modification to those agreements; and, of course, the communities in which the people working at the site live. In some cases, assessments may need to focus "inside the fence," while in others, the dependencies upon external systems that are themselves deemed vulnerable may be so great that meaningful conclusions cannot be reached without including these external systems. Bounding is important for assembling the assessment team, including stakeholders and subject matter experts.

Collection and analysis of existing information is an important objective of this initial step that enables the assessment team to learn about facility-specific conditions that affect its sensitivity and adaptive capacity. Initial information collection can establish the overall condition of infrastructure or ecosystems and current capacity for preventing, managing, or recovering from damages or disruptions related to climate. Existing information can also identify baseline climate impacts from current climate (mean conditions and extreme events), specifically on operation and maintenance costs. Importantly, it can also identify upcoming decisions that would benefit from information about climate change and its significance. Examples of some of these decisions are those related to recapitalization and construction of infrastructure, changes in operating margins or safe conditions, and responses to changing trends in outages, damage, service calls, cancellations, and operating restrictions.

The information sources we were able to use included master plans, other required reports or plans (for example, related to natural resources management on the facility), geographic information system (GIS) data, mission dependence databases, real property databases, service records or contracts, summary reports of damages/recovery times/adaptations made from past extreme climate events, vulnerability assessments of external systems, and others. Webinars, structured interviews of key personnel, questionnaires, data calls, and other techniques can play a role at this stage in bounding and information gathering. Analysis of the preliminary information gathered may employ a range of techniques, including use of some of the same models that will subsequently be used with climate change projections to assess future impacts and vulnerability.

This analysis enabled the analysts and researchers to develop some "priors" or starting points for discussion about which systems are vulnerable, and to prepare read-ahead or presentation materials to share with facility operators and managers during the site visit (see next step). Having a foundation of analysis of existing information provides focus and enables the next phases of the assessments to move ahead more efficiently. The importance of step 1 preparations cannot be overstated.

Step 2: Confirm/Revise Preliminary Evaluation and Set Priorities for More Detailed Analysis

The purpose of this step is to update and refine understanding of installation baseline conditions and to make decisions about the next steps of the assessment process. Activities include obtaining feedback on preliminary analysis prepared in step 1, more detailed appraisal of conditions, gathering additional information, and agreeing on expected products and next steps. Interactions at this stage provide an opportunity for managers and operators of different systems or activities and at different governance levels to exchange information and develop a shared understanding of assessment priorities going forward. Supplemental information gathered at this stage enhances understanding of baseline conditions, including changes in infrastructure location or use, current conditions, past damages from storms or other climate conditions, management and emergency preparedness measures, and planned future expansion or recapitalization. In our experience (which occurred during site visits), information gathered during step 2 was crucial for correcting misimpressions based on existing sources that occasionally reflected prior rather than current conditions.

For most sites that are deemed of sufficient priority to warrant an assessment, at least one site visit will be required to facilitate interactions between facility stakeholders and technical participants conducting and supporting the assessment. An initial site visit may fill a number of purposes, including obtaining feedback on the initial analysis described previously, more detailed appraisal of conditions, collecting additional information, and agreeing on expected products and follow-up. During our site visits, we found it helpful to provide an presentation on potential changes in climate and their impacts based on information collected and analyzed before the visit. It can be valuable to gauge initial mental models of users regarding climate change, present basic information, and develop a more precise understanding of what aspects of climate will require additional analysis.

Information on the characteristics of the facility, such as condition of buildings or other systems, and past damages from storms or other climate conditions can be a good initial indication of vulnerability to potential changes in climate conditions. While some of this information may exist in centralized databases such as real property management systems or condition indices, our experience was that the expert knowledge of individuals who operate the facilities and thus know them best is essential to develop an accurate picture of facility characteristics. Personnel are also best able to identify thresholds in climate-related conditions or events, which, if surpassed, lead to damage.

A site visit also provides an opportunity to gather information on the effectiveness of current management and emergency preparedness measures for coping with ongoing weather and environmental hazards, as well as identifying opportunities for adjustments in practice or alteration of infrastructure at the time of planned modernization or facilities expansion. This information is important in its own right, as it contributes to understanding sensitivity. It also focuses and bounds the information that is needed about exposure, which in turn can be useful in selecting data and analysis methods appropriate for providing this information.

Crucial outcomes of a site visit are building trust among participants, preparing a draft list of identified vulnerabilities, and agreeing on next steps including the modeling and analysis that may be required, outputs of the next stages of analysis, and how the outputs will be incorporated in additional engagement processes such as scenario planning or charrettes to assess the significance of potential impacts.

Site visits can be held over one or more days, depending on the complexity and size of the facility. Alternatively, visits may be held as a sequence of shorter sessions that focus on one aspect of the facility at time. Factors that affect how best to organize site visits include preferences of stakeholders, proximity of the facility to researchers and analysts, budget, and other practical factors. See Section 4.3 for a more detailed discussion of engagement methods appropriate to different assessment circumstances.

Step 3: Analyze Future Climate Exposure

By this point, steps 1 and 2 will have resulted in an improved understanding of baseline conditions, identification of further information needs, and priorities for analysis. This step adds another important pillar of information needed to project potential future impacts: future climate exposure. As illustrated in Table 2, potential impacts from current variability and potential future changes in climate arise from many complex climate and environmental phenomena. Our case studies demonstrate the need for climate information to go beyond the standard climate model outputs of temperature and precipitation and include issues such as fire risk, wind speeds, air quality, runoff, temporary surface flooding, erosion, and changes in tropical/extra-tropical storm frequency and intensity. Analysis of exposures needs to employ a wide range of techniques and information sources, including linking climate models with hydrological, atmospheric chemistry, storm surge, and other models. Approaches to providing information on specific types of impact-relevant exposures need to be more systematically considered by the climate science community, and additional technical guidance about sources of high-resolution climate information is being developed by SERDP. An approach that we have used in our case studies and believe holds promise is to identify priorities for information on exposures important in a particular region or facility type and to prepare “climate change outlooks” (see Section 4.3) that provide data and interpretive analysis, including confidence levels and discussion of sources of additional information and data. Such interpretation is key, especially considering model and scenario differences and highly varied levels of confidence across variables and regions. Section 4.3 contains a more detailed overview of methods for developing relevant information about exposure.

Stakeholders and many climate analysts assume that the best information will come from the highest resolution models, but this may not always be the case: analysis of large data sets containing many climate model simulations (“climate model ensembles”) developed using coarser grid climate models may provide more robust or reliable information because these data sets provide a better foundation for analysis of return periods (estimated time interval between similar events) or other statistical characteristics. This is partly because, at this time, the computational requirements of the highest resolution models do not permit development of large ensembles of model data for analysis.

Step 4: Estimate/model Potential Impacts

The objective of this stage of the process is to translate changes in climate (exposures) into changes in the operation or condition of engineered infrastructure, ecosystems, natural resources, or other inputs required for a facility to achieve its missions. A wide range of analytic approaches are available. Our case studies included use of: event history analysis to examine damage from historical climate and consider potential future impacts); return period analysis of flooding; GIS tools to study potential coastal inundation; a three-dimensional coastal ocean model with a detailed representation of the land surface coupled to a climate model to model storm surge impacts; projections of fire risk and heat stress indicators using regional climate model data; network interdependence analysis; projections of change in heating and cooling degree days; and decision trees. Many additional methods are available at varying levels of complexity and expense, and selecting which ones to use will depend on the needs of participants and the resources/time available. At the simplest level, analysts may consult research studies or reports that have already been completed to assess impacts on similar types of assets, adapting the insights of these studies for the case at hand.

Impacts modeling will not be needed for all facilities or systems, but it is possible and often advantageous to adapt existing models to produce quantitative information on potential impacts for mission-critical systems. As will be discussed in Section 4.3, a wide range of climate change impact models has been developed and is available for application. These models are not often systematically tapped to provide impacts-relevant climate inputs to vulnerability assessments. Identifying methods, learning from their application, and further improving them would benefit from a systematic approach to cataloging and evaluating the use of climate model archives to produce derived impacts-relevant climate data for use in assessing vulnerability assessments. Federal agencies are in an excellent position to collaborate and provide leadership.

Step 5: Evaluate Significance and Agree on Next Steps

The significance of potential impacts identified by the process up to this point will need to be determined through discussion with stakeholders at the relevant governance levels. An example might be that, having determined that the number of days suitable for controlled burning will fall below requirements to maintain good ecosystem health, what are the implications for continued viability of certain types of training (for example, maneuvers with heavy equipment) and potential changes in the approach to ecosystem management? How would the installation be able to change its ecosystem management approaches to adapt, or would it be necessary, given projections and limited adaptation potential, for the DOD Service to consider relocating some training activities to other installations in the longer term? This stage of the process is especially valuable for bringing different governance levels together to exchange information and perspectives.

Significance of potential impacts will vary, making a variety of responses appropriate. One outcome may be to identify the need for additional monitoring to track whether changes in climate and impacts are sufficient to warrant further action. Another is to alter ongoing management practices to better align system operations with evolving conditions. Other options may require adaptations such as recapitalization of existing infrastructure or investment in new systems, thus requiring tier 3 analysis adaptation design .

Decisions about the methods to use to assess significance must be driven by the level of perceived relevance and importance of climate impacts and the interests of stakeholders. Approaches can include one-on-one interactions, focus groups, design charrettes, scenario-building, or any combination of these activities. The degree of requested stakeholder effort should be matched to expected value added and degree of influence on decisions. Linking the discussion of vulnerability to adaptation that will increase resilience can provide an incentive for participation.

Conduct Assessments to Support Ongoing Planning, Budgeting, and Decision-making Processes

Potential climate change impacts can affect many ongoing decisions, both near and long term. Near-term decisions include scheduling, environmental compliance, ecosystem management, contractual arrangements for maintenance, and others. Some that require substantial investments are planned far in advance and long-lived. These include decisions related to siting and specifications for buildings, road networks, infrastructure systems such as electricity and water, and natural resources such as training and recreation areas. We found some longer-term plans being developed that would increase the risk to a facility from future climate change.

Our initial approach to using the results of our assessments was to attempt to apply decision analytic techniques to explore the implications for individual infrastructure-related decisions. These are time- and resource-intensive methods, and they require access to information about both official and informal decision-making processes and influences that can be sensitive and difficult to obtain.

As a result, for tier 2 vulnerability assessments, we began searching for ongoing decision-making processes in which we could incorporate information about potential impacts and vulnerabilities. For example, for DOE and DOD, we identified a number of potential decision types and planning processes that are used to plan acquisition, design, construction, operations, and maintenance of equipment and buildings. These include development of facility master plans, periodic preparation of natural resource management plans, development of unified facilities criteria, and others. These processes – which develop and/or update the vision and/or mission for the facilities and identify new infrastructure or systems needed to fill gaps between current systems and those required for mission attainment – are required for ongoing decision making. Because they are updated periodically, they provide unique points of leverage for improving on the potential to mitigate climate change impacts and reduce or eliminate vulnerability into the design of these facilities.

Vulnerability assessments should be planned to provide information used in these processes. As noted in Table 1, climate information provides an essential input to vulnerability assessment but is not sufficient to inform decision makers. To be relevant, vulnerability assessments must produce information that directly relates to factors and criteria that facility managers, planners, and officials currently use in making decisions. This includes information related to potential impacts on costs, reliability, encroachments, compliance with health and safety, or environmental regulations, sustainability, and other factors. Additional research is required to identify points of leverage as well as to train participants in these processes on the uses and limits of the information being provided.

Document Results to Provide a Baseline for Future Assessments

Careful documentation of assessment results provides a foundation for any subsequent assessments that may be conducted at a site. Having a baseline of prior results facilitates evaluating how conditions are changing as a result of either change in climate conditions or in response to adaptation measures that are implemented. Documentation and evaluation of the process fills another role. Climate vulnerability assessments are still a new activity, and improvements in the efficiency and usefulness of the process are needed. Facilitating revisions to existing frameworks and innovation to develop new approaches – such as self-administered assessments using online decision support systems – will require agencies to document the processes and results used on different sites in a systematic and comparable fashion. Development of a protocol to evaluate, learn from, and revise assessment processes is in itself an important research task. Questions related to the effectiveness of methods, participatory and engagement processes, and outcomes need to be developed and answered. For example, were bounding and framing effective in prioritizing without excluding consequential vulnerabilities? Was the modeling and evaluation of exposure and potential impacts conducted sufficient to provide information that participants found relevant and useful for understanding the potential significance of changes in climate to their facility's mission attainment? What engagement and communication techniques facilitated learning by participants? Was information incorporated into ongoing processes, and if so, were decision outcomes affected? Possible components of systematic evaluation include careful documentation of the process used in each case, questionnaires and interviews with participants, and data collection to compare projected impacts with those that occurred. It would be advisable to develop a template for documenting and evaluating assessment processes at an interagency level, to facilitate learning and improvements in methods available.

4.3 Three Sets of Methods Needed for any Vulnerability Assessment

In conducting our case studies, and looking across the steps of our prototype vulnerability assessment framework, we identified three core tasks that were essential at each facility. We offer this typology as a possible approach for organizing methods and assessing their effectiveness because they are potentially relevant to any vulnerability assessment of a facility or site, irrespective of the detailed assessment framework that is employed:

1) **Engagement:** Engage personnel with detailed knowledge of the mission and operation of the facilities to (i) provide the information about their condition and characteristics and (ii) aid in interpreting the significance of identified impacts for their management tasks

2) **Climate exposure:** Prepare tailored information on exposures, drawing on several sources of information including observations, projections, and scenarios of climate conditions, downscaling, and modeling of hydrology and other related environmental conditions

3) **Future impacts:** Project impacts using diverse quantitative and qualitative methods.

Table 3 crosswalks the methods to the steps in our assessment framework. In the sections that follow, we briefly characterize these methods and suggest resources for further information.

Engagement

These methods are designed to involve stakeholders in the assessment process, through initial and continuing interaction, to determine priority risks and evaluate their significance for a site or facility. Research has repeatedly shown that agreement among participants in such a process is necessary to produce knowledge recognized as useful to decision makers. This is sometimes characterized as an information problem (for example, Oreskes and Conway, 2011), a communication problem (for example, Moser and Dilling, 2007), a framing problem (for example, Marshall, 2014), an instance of the so-called science-policy gap (for example, Dilling and Lemos, 2011; Rogers and Gulledge, 2010), or as a problem inherent in the climate issue (for example, Jamieson, 2014, Rayner and Prins, 2007). Likely all of these factors play a role in the willingness of facility personnel to engage. At facilities where there are current climate-related impacts, personnel may be ready for productive engagement.

Engagement methods must be selected for specific situations in which (1) climate change is salient to facility personnel (in other words, they see a connection between climate change and the future operation of the facility), (2) the potential exists to establish interest and a change in mindset to incorporate climate change as a risk factor to be considered along with others, or (3) climate change is not seen as salient to the facility or the duties of its personnel. Engagement methods are useful for creating opportunities for stakeholders at any of the governance levels considered in the study (DOE Headquarters, DOE Office, and facility; DOD Headquarters, DOD Service, and installation) to collect, exchange, and organize disparate information, and to evaluate the significance of projected changes for current and future plans.

Table 3. Methods used in vulnerability assessment framework

(Key: VA=vulnerability assessment) The following table demonstrates how the cross-cutting categories of methods (columns in the table) are used throughout the steps of the vulnerability assessment process (rows) described in this paper. For example, the vulnerability assessment team should design engagement methods (such as focus groups or charrettes) to help in reaching a mutual understanding of the requirement for a vulnerability assessment and its use for the facility (the first row) and in establishing boundaries for the vulnerability assessment (second row). Also important for bounding the assessment would be using exposure characterization and results from prior impacts analysis (for example, in community or regional area assessments) to determine how wide the boundaries should be —that is, what operations will be affected and how impacts could have indirect as well as direct effects.

Categories of Methods / *Steps in VA*	Engagement Methods	Exposure Characterization Methods	Impacts Analysis and Modeling Methods
Establishing Requirement/Use of VA	✔		
Bounding/Framing	✔	✔	✔
Site Visit(s)	✔		
Tailoring Information on Exposure		✔	
Estimating Impacts		✔	✔
Determining Significance and Next Steps	✔	✔	✔
Supporting Ongoing Decision Making	✔		
Documenting and Evaluating	✔	✔	✔

Data collection methods are needed in all cases, but in some circumstances (when salience is lacking), data collection may be the primary focus of involving stakeholders, as there may be no interest in participating in any methods designed for engagement. As described previously, information collection focuses on gathering a wide range of information about current impacts, condition, mission importance, exposures with the greatest risks, thresholds, and upcoming investment decisions.

For the purposes of engaging facility stakeholders, the research literature provides "how to" guidance at two levels, and specific tactics are provided by myriad business and organizational experts.

First, the mode of engagement should be considered. Meadow et al. (2015), assessing methods for coproduction of knowledge, use Biggs' (1989) structure of four modes:

- Contractual, where researchers are testing new technologies or knowledge and stakeholders are primarily passive recipients
- Consultative, where stakeholders and researchers consult to diagnose and solve a problem, but stakeholder views are primarily filtered through a third party
- Collaborative, where stakeholders and researchers directly partner to work on a problem
- Collegial, where the goal is to build local stakeholder capacity to solve problems.

Second, specific approaches for conducting engagement are analyzed by Meadow et al. include Action Research (a collegial mode), Transdisciplinarity (a collegial mode), Rapid Assessment Process (consultative or collaborative mode), Participatory Integrated Assessment (consultative, collaborative, or collegial mode), and Boundary Organizations (consultative, collaborative, or collegial mode). Other, related schema can be found in Lim et al. (2005). The intensity of involvement depends upon the length of the task (from a one-time meeting to a continuous collaboration), the context (resource constraints, importance and size of the task, etc.) and the desired mode (collaboration and collegiality demanding more time and commitment than other modes).

At the tactical level, engagement with stakeholders can be via (1) meetings, (2) webinars or other forms of training, (3) data calls and GIS maps/discussions, (4) one-on-one interactions, (5) focus groups, (6) design charrettes, (7) scenario-building, (8) workshops, or (9) any combination of the above. The degree of requested stakeholder effort should be matched to expected degree of influence on decisions or some other incentive, and there is a need to establish roles, competencies, legitimacy, and trust in any engagement process (Cash et al. 2006).

Here, we provide some analysis of our experiences with engagement of facility personnel.

The need for a wide range of engagement methods

One of the most important cross-cutting observations from our case studies is that not all personnel could see the value of a vulnerability assessment process or how they would be able to change management or justify additional expenditures for adaptation given the large uncertainties in climate information. Given the range of concern, it is essential that those conducting facility-level assessments have available a range of engagement methods. Where climate change is a priority, these methods can include a variety of interactive approaches that encourage information exchange and brainstorming of adaptation options. Where it is not, methods need to focus on collecting the information and providing information and measures that are useful and easy to implement, given the audiences and their purposes.

A variety of approaches for effectively communicating what is understood about climate change to different audiences needs to be developed. These approaches need to help participants move beyond expectations of precise, deterministic "forecasts" of future climate conditions to enable them to work with uncertain but still informative climate data through use of scenarios, ranges, probabilistic information, and other approaches.

Factors promoting participation

Successful facility-level vulnerability assessments require a "champion" who can ensure that key personnel participate. This leadership can come from a headquarters office or from a person in a position of authority at the facility. We observed that information collection and salience were greatly affected by the degree to which an accepted authority indicated the importance of participation in the process. Engagement was more successful in collecting information and contributing to learning at sites where operations and maintenance staff held their positions for longer periods. There was more institutional memory of the effects of past extreme events, making it possible to verify and correct information collected from existing reports or databases. Candid participation of personnel can be encouraged by not attributing comments to specific participants. This can be especially important when attempting to identify problems that could make a system more sensitive to climate change, and in evaluating characteristics of adaptive capacity related to leadership or openness to climate change.

Sources of information

Data from existing Office-, Service-, or department-level information systems (for example, mission importance ranking, real property databases) and available reports (for example, installation master plan, integrated natural resources management plan – INRMP) required verification. Our intent was to use these existing systems to better understand asset condition, mission importance metrics, past damages, planned expansion or recapitalization, and other factors that would provide insight into sensitivity or adaptive capacity, thus reducing the information collection burden on staff. Our experience was that the department-, Office-, or Service-level databases were of limited utility due to incomplete or inaccurate data. Similarly, even information from installation-specific reports such the INRMP may be outdated and thus require verification during a site visit.

Records maintained in a facility's public works department, natural resources management office, health center, operations center, and the like can also be valuable. This information can include training cancellations, number of heat stress incidents, damages arising from specific storms, frequency of deployment of preparedness or response measures, clean-up costs, and the like. In our case studies, we attempted to gather such information and correlate observed damages with meteorological records of routine (but still damaging) incidents or more severe but rare events. Unfortunately, we discovered, at least in our small sample of sites, that while basic information about such impacts was recorded, for example, about the dates on which a training area might be closed, information required to attribute the cause of the impact was not – for example, was the training area closed due to flooding from a combination of high tide and storm surge, or from a temporary encroachment? Some relatively minor changes in procedure could lead to collection of such information, which over time would facilitate improving resilience.

Thresholds and adaptive capacity: Assessment challenges

Identification of thresholds – levels of a phenomenon at which a system is disrupted or damages increase disproportionately – was more challenging than anticipated for many systems. For some, such as water resources, clear combinations of stresses will endanger reliability of performance. If identified, a more robust use of climate information is to examine large ensembles of climate model projections to identify the frequency with which these conditions are met or exceeded over time – are the thresholds crossed more frequently? Identification of thresholds in our experience was often difficult, as damages or disruptions often occurred as a result of combinations of climate and other conditions, making attribution to specific climate conditions impossible.

Assessment of adaptive capacity was similarly challenging. Adaptive capacity depends on many factors that vary in importance from case to case. Availability of financial resources, trained personnel, clear emergency preparedness plans, and other factors can be assessed in a straightforward fashion. Other facts, such as organizational culture, leadership, or informal budgetary flexibility to respond to the unexpected, are more subjective, difficult to assess, and not appropriate to discuss as verification can be difficult.

Climate Exposure

Many sources of climate information can be useful in vulnerability assessments, and it is not possible in the context of this technical paper to provide an overview of these sources. The recently completed Third U.S. National Climate Assessment (NCA3) produced and disseminated several climate scenarios and information products (Moss et al., 2011; Kunkel et al., 2015). A series of regional reports and visualizations including more than 700 pages of material and several hundred graphics on past trends and future projections was prepared and made available for the eight National Climate Assessment regions. These, along with other Federal global change data, information and products can be traced in an open-source, web-based resource called the Global Change Information System (data.globalchange.gov). Projections for NCA3 used data from global climate models (GCMs), dynamical downscaling (regional climate models [RCMs] of higher resolution for global regions), and statistical downscaling of both observations and GCM output. In addition, the National Oceanic and Atmospheric Administration and other agencies have collaborated to produce a "U.S. Climate Resilience Toolkit" that includes links to several data sources such as "Climate Explorer," "Climate Inspector," "Climate Wizard," and others. Some of these portals provide data that has been evaluated for its intended uses, while in other cases, scientific quality and or the appropriateness of the information for specific uses has not been evaluated.

The purpose of this section is to describe the approaches used for analyzing and communicating exposure for our vulnerability assessment case studies, developed in collaboration with the National Center for Atmospheric Research.

Climate outlooks

To prepare information on exposure for use in our vulnerability assessments, we adopted an approach used in the 2007 Intergovernmental Panel on Climate Change report to evaluate and make qualitative likelihood statements regarding changes in regional-scale precipitation (Christensen et al., 2007). As just mentioned, a similar approach was used concurrently in the NCA3 to prepare a set of eight regional climate change outlooks. Our vulnerability assessment case studies were selected to be from a single region: the mid-Atlantic region. This allowed us to test whether it was possible and effective to prepare a single, common source of information for use in assessing vulnerability of sites in the region.

The outlook describes conditions that have in the past or are likely in the future to interact with facility vulnerabilities to produce impacts. The specific aspects of climate to be investigated and discussed were identified through the process of framing the assessments and conducting the initial site visits. The outlook includes narrative textual analysis, graphics, and other information; it is based on observations, GCM and RCM results from several large research projects that compile and compare models results, and other knowledge from basic climate research on climate conditions and processes in the mid-Atlantic region. The rationale is that by integrating and evaluating these multiple sources of information, the outlook will offer more robust understanding than when any single information source is considered independently. An expert judgment approach is used to evaluate the available information and provide ratings of confidence that can be associated with different findings.

We note that while standardized information from the outlook was relevant to many of the issues that arose on the studied sites, tailored information developed specifically for each site was also needed. This information often used local observational records or focused analysis on interactions between global/regional trends (for example, sea level rise) and local conditions that would create anomalies. If a climate outlook for sites in a region (or of a certain type) were viewed as a "living document" and new analyses conducted for individual sites were incorporated and included information on methods, the outlook could become increasingly useful.

Evaluation of the climate outlook is ongoing, but evidence in the literature (PROVIA/UNEP, 2013) indicates that narrative descriptions of past and future climate conditions are effective at communicating with stakeholders. They make complex, quantitative data easier to understand, can clarify the sources and significance of disagreement in projections across different models or methods, and provide a subjective evaluation of confidence for use of the information in decision making.

Tailoring climate information for impacts modeling

As illustrated in Table 1, the process of assessing vulnerabilities and potential impacts requires the tailoring of climate information into specific impact-relevant climate variables that are not the usual focus of climate model analysis. Example impact-relevant variables identified through interaction with stakeholders at our case study sites included wet bulb globe temperature, heating and cooling degree days, fire potential, changes in the frequency of severe thunderstorms, and surface wind speeds. Variables relevant for sites in other regions will no doubt differ, and indeed, as more sites are engaged in the mid-Atlantic region, additional variables and processes will no doubt be identified. In many instances, assessment of impacts and significance requires estimation of changes in the frequency and/or intensity of the impact-relevant variables, and numerous sources of information exist, including the types of modeling and downscaling described previously.

Different sources of information and analysis methods have different biases, strengths, and weaknesses for application. Weather generators and other approaches such as the "delta method" (in which projected changes are added to observed climate data) are widely used and appropriate for some applications. It is not always the case that the highest spatial resolution models are the best source of information. In some cases, additional models will be needed. For example, we used the Finite Volume Community Ocean Model (FVCOM) to study coastal estuarine flooding/drying processes.

The latest National Climate Assessment report contains a synthesis of a variety of climate model information, including, average annual temperature, length of the frost-free season, hottest and coldest days, number of extremely hot days, average annual precipitation (average and extreme), extreme weather (that is, the thunderstorm environment), hurricanes, and sea-level rise (Melillo, Richmond and Yohe 2014). From a decision support perspective, these variables are limited in their applicability and usefulness in that they do not directly map onto existing decision support activities. Instead, translation of these variables needs to occur before they can be incorporated. A variety of approaches are available to map the raw climate model output onto changes in the exposure variables of interest: for example, the FVCOM used to study coastal estuarine flooding/drying processes; techniques such as extreme value statistics (that is, return periods); or indexes, such as the Keetch-Byram Drought Index (KBDI) which measures fire potential. Changes in exposure can then be used to assess consequences and provide support for decision making.

Future Impacts

Vulnerability assessments require a wide range of methods for analyzing observed impacts of weather and current climate, as well as projecting potential future impacts resulting from climate change. This section introduces the need for an approach for organizing and analyzing the suitability of available methods for impacts analysis in the context of vulnerability assessments for Federal sites (see PROVIA, 2013 for a description of some of the methods relevant for national to community scale vulnerability assessments; we are not aware of a methods compilation for infrastructure or facility-oriented assessments and recommend that such a compilation be developed as a resource for those conducting assessments at Federal sites). This section does not provide a detailed typology of impacts models or results from the modeling experiments we conducted in the context of our research. More detailed information about results and assessment of methods will be contained in the final report of the project funded through the SERDP.

Analysis of *observed impacts* involves detecting a change in an impact variable of interest and examining whether there is a statistical relationship with changes in weather or climate. “Impact variables” can vary widely from quasi-climate variables such as heating or cooling degree days and flood return periods to variables related to resources or infrastructure management, such as water reservoir depth, storm damage, electric grid capacity exceedance, or operating costs. In analyzing trends in these variables, it is essential to employ rigorous statistical methods and to consider potential drivers of change beyond climate events, as multiple causative factors can be changing simultaneously.

Projection of impacts focuses on a similar set of variables but adds the complication of using information on potential future climate conditions, from quantitative climate scenarios to more qualitative descriptions of changes in impact-relevant climate exposures. In some cases, quantitative analysis of performance of systems or effects on ecosystems and other “natural assets” will be possible using a variety of impacts models that address sectors such as water resources, energy supply and use, ecosystem composition and condition, transportation, and training activities. Additional uncertainties on top of those inherent in projecting future climate are involved when adding environmental process (e.g. hydrology) and impact (e.g., damage curves) models to the analysis. These uncertainties result from limited understanding of environmental processes, model incompleteness, uncertain parameterizations, and other factors. Little work has been done on matching the impact model input variable requirements and their spatial and temporal constraints to the available climate information.

Models used in ongoing management and planning can be used to project a wide range of system functions and conditions, for example, runoff and potential flooding, energy demand, and stresses on building or transportation system components. Modeling the impacts of climate change on resource management and infrastructure systems is inherently complex, and in deciding to undertake impacts modeling, it is crucial to explore application of models already in use, such as the Federal Energy Decision System (FEDS) model, which is used in assessing temperature-sensitive energy loads for different building types (see Scott et al., 2008, for an application focused in interactions of changing climate conditions and energy efficiency programs). Use of existing system models to evaluate impacts is useful when imposing possible future climate conditions on existing systems to evaluate the performance. For example, an existing transportation network model may consider how changes in extreme precipitation lead to increased disruptions and travel times.

Many examples of these kinds of methods are found in the literature and in technical reports. For example, Filadelfo, Mintz, Carvell, and Marcus (2012) use projected temperature changes to 2040 relative to the 1995–2011 17-year mean to approximate the change in installation energy demand using heating and cooling degree days. The relationship between the degree days and the energy used were based on regression analysis of historical system performance. The authors downscale large regional-scale climate change projections for the immediate areas of several military installations including Fort Bragg and Naval Station Norfolk. Another example is described in Domingo et al. (2010), where a Mike Flood model is developed for a coastal community and then used to simulate flooding from a derived extreme sea-level event. Instead of focusing on modeling the impacts themselves, other methods focus on evaluating the anticipated impacts from climate change under different scenarios. For example, Lambert et al. (2011) assess the impacts on transportation infrastructure via a decision model to help prioritize elements of a long-range plan in the area around Hampton Roads, Virginia.

"Decision scaling" methods, described by Brown and Wilby (2012), are approaches that, for a given system performance measure or objective, use a stress test to identify the hazard and evaluate the performance of a system under a range of nonclimactic and climatic variability and change. They then evaluate the risk the system using climate model information. These methods have the potential to preclude climate impact assessments if, for example, a stress test is performed and no risks emerge under a wide range of plausible climates. We tested a diverse set of methods in our research, including the following:

- Statistical analysis of climatology to evaluate the changing spatial pattern of flooding return periods
- Using a coastal storm surge model to evaluate the spatial impact of future storms under different sea-level rise projections
- Analysis of the interdependency of systems at a facility using network analysis and statistics
- Analysis of changing fire risk to determine how it may impact the availability of burn days necessary to manage an ecosystem
- Evaluation of possible changes in energy use through analysis of changing heating and cooling degree days.

Going forward, it would be beneficial to organize resources for impacts modeling methods at Federal sites along sectoral lines, even though there are important cross-sectoral interdependencies that should be addressed in impact modeling. These sectors could include the following:

- Energy demand, capacity, and distribution
- Water resources
- Transportation systems
- Waste and wastewater systems
- Information systems
- Ecosystems (for example, forests, aquatic, and coastal)
- Human health (for example, effect of heat stress)

A careful review of existing models appropriate for Federal sites is needed to evaluate their compatibility to use as inputs to existing climate model projection information. For example, some hydrological models used for riverine flooding require data inputs that are currently unavailable from climate models. Such a review would provide a starting point for managers and decision makers in understanding how future climate change may impact their managed assets.

5.0 Tier 3: Adaptation Design

For completeness in describing the elements of the tiered process, we briefly discuss the purpose and character of "Tier 3 – adaptation design." Our intent is not to recommend specific adaptation design methods but rather to conceptually distinguish this level of analysis from installation vulnerability assessments. Some practitioners consider design of adaptation options to be distinct from vulnerability assessment. We include it in this framework to emphasize that additional evaluation and planning beyond that contained in a climate vulnerability assessment is frequently needed to design/plan and implement adaptation. Tier 3 is especially relevant for structural adaptations, whether hard (infrastructure based) or soft (e.g., ecosystem based), but additional analysis of management and other systems can also be needed for non-structural options.

Tier 3 focuses on a detailed evaluation of various technical or policy adaptation options to address specific vulnerabilities identified in the tier 2 assessment. For example, if the tier 2 analysis reveals increased vulnerabilities resulting from changes in water height associated with the 100-year flood under a number of scenarios, then this range of flood height increases would be used in conjunction with traditional engineering analysis to evaluate the effectiveness of different flood wall designs and heights. Tier 3 analysis may extend the boundaries to include economic externalities and to focus on detailed scenarios. Tier 3 may develop an integrated risk management strategy or determine a range of options for modifying existing built infrastructure, siting of new construction, or developing new maintenance and repair procedures to protect against specific climate change impacts.

Infrastructure is often a critical focus of adaptation design. Buildings and other infrastructure are an obvious category of elements that require substantial investments and planning: infrastructure and associated systems are planned far in advance of construction, long-lived, necessary for the agency missions, and potentially vulnerable to climate change—but, also, potentially resilient in the face of climate change. During adaptation planning, vulnerability to climate change is considered along with other risk factors so that optimal decisions can be made about future capabilities, missions, configurations, and operations. Moreover, decisions about infrastructure are iterative; that is, once a factor (for example, sea-level rise) that needs to be considered is included in planning, updates to planning can include updates to the vulnerability assessment. In many cases, incorporating climate risk into ongoing design and planning may require developing "a new paradigm for engineering practice" to account for uncertainties in information about the risks and potential costs of changes to a project (Olsen, 2015, p. 62).

At the timescale used in infrastructure planning, questions of thresholds arise. Current workarounds may be sufficient to cope with existing climatic events, such as clean-up procedures for nuisance flooding or controlled burns to manage the risk of wildfire. But, for instance, at what point in the future will it be too expensive to disrupt schedules, pay for cleanup, and make up training time? What are the implications of more frequent interruptions of flights or exercises? What would make the ecosystem incapable of supporting training—increasingly dry and hot conditions? How should agencies "design in" adaptations to sea-level rise? In short, when will a site or facility be spending more resources on workarounds than is feasible, unless decision makers plan for resilience through adaptation? Scenario exercises and analyses can point to needs for changes that will benefit future mission fulfillment at the site.

As planners and managers go through the process of adaptation design, the answers to such questions take on practical considerations including siting, design criteria, and compatibility with other requirements, such as sustainability. To evaluate feasibility, options, and mission-readiness, planners and designers may conduct detailed engineering studies, analyze existing arrangements (contracts, agreements with utilities or communities, overall configuration of the site, training schedules, etc.) to see if they need to be revised, and look for opportunities to improve both mission capabilities and operations.

6.0 Conclusions and Next Steps for Developing Vulnerability Assessment Methods

Federal agencies are responding to instructions in Executive Orders to prepare for changes in the climate by assessing the vulnerability of their infrastructure assets. This paper has described a framework for vulnerability assessment that includes three tiers: (1) screening to identify and select facilities and sites most at risk from the impacts of climate change, (2) facility-focused assessments of specific risks, and (3) detailed design of adaptation options to address those risks.

Recent case studies conducted by Pacific Northwest National Laboratory explored methodologies for facility-level assessments. This technical paper synthesizes results and experience in our research for the purposes of sparking discussion and feedback. It presents a framework of steps for assessments at DOE and DOD sites that may be appropriate or adaptable for facilities, infrastructure, and sites managed by other agencies. The paper also elaborates on three sets of methods essential to any vulnerability assessment process: engaging stakeholders, providing tailored and usable climate information, and linking information on climate impacts to specific missions and operations so that existing planning and other decisions can account for such impacts. We argue that methods development could be accelerated through a more concerted process to identify and compare methods in these categories.

Conclusions from our assessments conducted to date include the following:

1. Vulnerability assessments provide essential and specialized information needed to determine the susceptibility and consequent risk of climate change to infrastructure assets. Federal agencies need this information to manage climate risks.

2. For the purposes of these assessments, "vulnerability" should be defined in a such a way as to focus on the characteristics of a site that affect its susceptibility to damage ("sensitivity") and its flexibility to adjust to novel climate conditions ("adaptive capacity"). This definition frames the challenge in terms that staff can understand, it structures information collection and analysis, and it directs the attention of staff to infrastructure that they can prioritize, measure, and manage.

3. Because many agencies manage a large number of facilities and assets that are potentially affected, a tiered assessment approach to setting priorities for detailed assessments and analyses will increase efficiency and reduce costs while still allowing for detailed analysis where needed. We propose a three-tiered approach: Tier 1 screens all agency sites to set priorities. Tier 2 focuses on more detailed assessments at a smaller number of sites identified as most vulnerable by tier 1. Tier 3 comprises analysis of adaptation options.

4. Because of the diversity of facility and asset types, a flexible but common framework for facility assessments (tier 2) is needed. Such an approach would provide adaptability for varied missions and operations but still provide a basis for comparative analysis useful to setting priorities for adaptation. The case studies suggest a process that would: (1) frame and bound the assessment through initial data collection and dialogue with stakeholders, (2) use site visits and other means to gather additional data and confirm the focus of next steps, (3) tailor information about future climate exposures focused on assessment priorities, (4) estimate/model potential impacts on prioritized systems/missions through methods that vary in complexity depending on mission importance, and (5) evaluate significance and next steps through stakeholder engagement. This framework should be implemented in any given assessment to produce information that is useful

for related planning and decision-making processes. To facilitate institutional learning, provide a foundation for future assessments, and improve climate vulnerability assessment methods, each assessment should be documented and evaluated.

5. There is no "one size fits all" approach for vulnerability assessments, especially for stakeholder engagement. Assessments must be adapted to take advantage of the expertise of staff who know how the installation works. Assessments can incentivize staff to integrate monitoring and adaptation planning into ongoing processes related to sustainability.

6. Information on future climate change needs to focus on installation- and area-specific variables, drawing on information sources including observations, projections, and scenarios of climate conditions, downscaling, and modeling of hydrology and other related environmental conditions. Projections should be made using diverse quantitative and qualitative methods.

The framework and process presented here have promise for future implementation, with (1) continued testing and evaluation of methods for screening, indicators, engagement, priority setting, providing climate information, estimating impacts and identifying thresholds, and determining consequences for missions; (2) assessment of opportunities to integrate climate change considerations into ongoing planning and decision-making processes; (3) development of training and technical guidance for participants and users of vulnerability assessments; (4) cataloging of available methods and establishing research programs to develop others; and (5) documenting and sharing of assessment experience to contribute to organizational learning within and across agencies.

In closing, some climate change impacts can no longer be avoided. The degree to which these impacts result in loss of life and damage to critical infrastructure and government functions depends on development and application of systematic approaches for assessing vulnerability and the use of the resulting information in planning adaptation measures to increase resilience. Information about climate change and its implications for facilities and operations of Federal agencies contains uncertainty, but it also contains valuable guidance for managing risks and developing strategies that perform well across the range of uncertain future conditions. Agencies can make better use of the available knowledge if they are active participants in accelerating research on vulnerability and decision making.

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Appendix A

Selected DOE and DOD Regulations, Orders and Guidance Relevant to Climate Change Vulnerability Assessments

Appendix A

Selected DOE and DOD Regulations, Orders and Guidance Relevant to Climate Change Vulnerability Assessments

- Buotte, P.C., J.A. Hicke, A. Peterson, C.P. Ischay, E.L. Fossum (2014). Climate Change Vulnerability Assessment for Idaho National Laboratory. Idaho National Laboratory: Idaho Falls, ID. Available at http://www.osti.gov/servlets/purl/1166046/.
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