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After the hurricane: Validating a resilience assessment methodology

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ABSTRACT

With increasing utility grid outages in the United States, there is growing interest in assessing risk and developing mitigation strategies to reduce the impact of grid outages. Working with the U.S. Air Force, the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) developed a replicable energy resilience assessment methodology and investment decision tool to: (1) identify and score hazards and vulnerabilities at the site level; (2) analyze risks to energy infrastructure; and (3) identify and prioritize energy resilience investments. This work improves on existing resilience assessment methodologies and tools by combining a bottom-up, all-hazards assessment methodology with top-down geographic information system mapping capabilities to provide an innovative, dynamic tool for identifying and prioritizing actionable solutions. This process combines probabilistic forecasting with an iterative approach for continuously updating and reassessing risks to address temporal dynamism. Relationships among systems are modeled and visualized to estimate the effectiveness of resilience actions across multiple interdependent systems and inform financial priorities through cost-difficulty-impact trade-offs. The approach is validated in a case study at Tyndall Air Force Base (AFB) in Florida, which experienced a Category 5 hurricane in 2018. The risks and mitigation strategies identified pre-hurricane are compared with post-hurricane, realized impacts. The assessment effectively identifies risks and actions to increase site energy resilience, but the methodology can be enhanced though greater consideration of the interdependencies between the energy system and related systems like transportation, communication, and food/water systems, which impact the recovery of the energy system and the base.

1. Introduction

With increasing grid outages in the United States, as illustrated in Fig. 1, there is growing interest in assessing the risks of power disruption and developing mitigation strategies to reduce the impact of electric outages on assets, organizations, and mission activities [1,2]. The U.S. Department of Defense (DoD), for example, views power disruptions as a significant risk to their operations. DoD has long relied on energy to sustain its missions; in 2015, DoD's installations consumed 1% of the total electric energy consumed in the United States [3]. Installations are critical to military readiness due to their support of weapon systems maintenance and deployment, troop training and mobilization, and, increasingly, direct support of combat operations; however, a 2008 Defense Science Board report found that DoD's reliance on a fragile national transmission grid placed critical missions at risk [4].

To effectively assess risks to site resilience and prioritize resilience investments, organizations like DoD require a resilience assessment methodology. Recent Executive Orders [5–7] focus on the need for U.S. government agencies to plan for adaptation and enhance the resilience of federal infrastructure and operations, and the need for operating and sustainability plans of most agencies to include climate change considerations [8]. The National Defense Authorization Act (NDAA) for Fiscal

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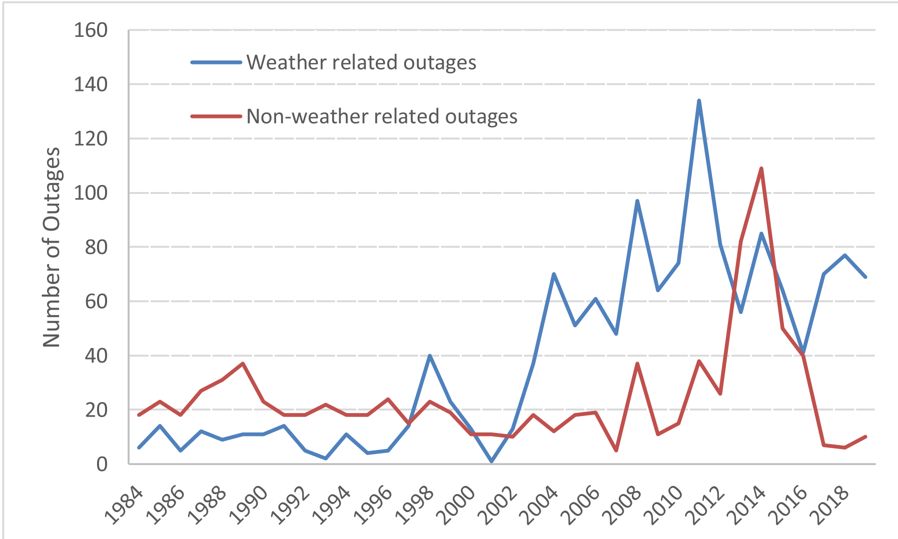

Fig. 1. Major power outages affecting more than 50,000 customers, 1984–2019. Source [1,2].

Year 2018 requires DOD to submit a report detailing the ten most climate-vulnerable installations for each service branch, and the FY2019 NDAA focuses on improving the resilience of DOD's built infrastructure and its electric grid by better accounting for extreme weather events, documented flood plains, and future sea level rise [9,10]. Given the 4800 sites DOD owns and/or operates worldwide [11], the task is enormous, and requires an efficient and systematic process for assessing risks and prioritizing mitigations.

There are a range of approaches for evaluating resilience across the domains of engineering, health sciences, sociology, economics, natural sciences, and spatial sciences. Engineering focuses on the resilience of buildings and infrastructure. Health sciences evaluates what makes individuals and community health systems resilient pre-and post-disaster. Sociology considers what makes social units resilient, and economics analyzes business resilience. Natural sciences study the properties of environments and their capacities to absorb shocks and rebound, while spatial sciences compare patterns and processes of resilience at local to global scales [12]. While a single standardized resilience assessment approach may seem desirable, many researchers assert that resilience is context-dependent and cannot be measured everywhere with the same variables and indicators [12,13]. Therefore, the literature on resilience offers a diverse set of methodologies, which fall into three primary categories: indices, scorecards, and tools [12,14–16]. These approaches can be applied at different scales to address different focus areas. Methodologies and tools vary in terms of the scale of system they cover, the hazards they address, their breadth and depth, qualitative versus quantitative measurement, and their focus on acute disruptions or long-term stressors. These resources can generally be classified as taking a top-down or a bottom-up approach [12,14].

Many of the top-down approaches focus on methods to measure the baseline characteristics of nations or communities that foster resilience, such that changes in resilience can be measured over time [17–26]. The top-down approach may consider physical, environmental, social, economic, political, and organizational aspects of communities. Some focus specifically on evaluating interdependences among systems [19,27–30]. Because they cover large geographic areas (ranging from a city to a country), these assessments are typically based on standardized datasets available at state, national, or international scales. This makes them well suited for comparing spatial variability, allocating resources, or monitoring progress across broad geographic areas from states to global scale. However, because they rely on broad datasets, they may be less detailed and lack local knowledge and information which is only found in highly localized data sources [12].

Other approaches [23,31] are more participatory, taking a bottom-up approach and relying heavily on qualitative methods such as interviews to assess infrastructure vulnerability. These approaches tend to be more rich and detailed because they incorporate local knowledge and information, and often have greater buy-in from the community that can result in more effective action [12], but are very labor intensive and can take more time to gather data. These approaches tend to focus on developing solutions to support resilience decisions and investments across scales ranging from national [32] to states [33] to local communities [34–36].

Geographic information system (GIS) data is commonly used to inform both top-down and bottom-up resilience assessments. Some platforms provide opportunities to share GIS data and models related to risk assessments, but do not conduct detailed resilience assessments themselves [37–41]. Other platforms incorporate GIS data to assess hazards and vulnerabilities and identify the highest-risk areas [42–52]. These platforms are used to inform planning and mitigation, but because they tend to focus on a single hazard, such as floods, tsunamis, or landslides, their scope is limited, and they may not provide a comprehensive assessment of all hazards in an area or the interaction between compounding hazards. Still others focus on recovery, providing a geospatial resilience assessment platform that assesses element-by-element recovery over time to indicate the degree of burden on emergency management resources, and how risk treatments can improve recovery times [53]. Mahmoud and Chulahwat (2018) produce resilience maps of a fictional city using an integrative model that analyzes six lifeline systems (housing, water, power, transportation, communication, and health) and their interdependencies [54]. A few recent techniques combine geographic information system and business intelligence software to provide location intelligence systems to assess flood risk [55] and speed recovery from disasters such as wildfires [56] by supporting decision-making during disaster management [57].

In a review of 36 tools for assessing community resilience, Sharifi (2016) found that many assessment tools lack stakeholder processes, loss estimation, information on potential savings from resilience actions, analysis of the effectiveness of resilience actions, use of probabilistic or future forecasting models, and scenario planning [14]. Sharifi found that effective tools should have appropriate scope and comprehensiveness, address cross-scale relationships, include temporal dynamism, address uncertainties, use a participatory approach, and develop an action plan. Sharifi concludes that few tools meet all the criteria, suggesting room for improvement.

Beyond these approaches in the literature, a range of methods and tools have been developed specifically for U.S. federal agencies. Larkin et al. review resilience assessment approaches in seven federal agencies [58]. The Department of Homeland Security (DHS) has a resilience framework and resource toolkit that provides a systematic approach for practitioners, policymakers, experts, and community leaders to assess and improve community health resilience from a system-wide perspective [59]. Further work has focused on building a resilience scorecard [60]. This checklist helps stakeholders recognize gaps in resilience to build a resilience score but does not specify mitigations. The Federal Emergency Management Agency (FEMA) provides a National Disaster Recovery Framework that outlines pre-and post-disaster checklists for specific stakeholders, providing recommendations from a system-wide perspective but no quantified assessment framework. The Office of Infrastructure Protection's Regional Resiliency Assessment Program provides a resilience audit that examines critical infrastructure from an all-hazards perspective. The audit provides recommendations for strategic investments to guide improvement of critical infrastructure resilience. This latter process is most closely aligned with the work presented here but is not available to the public.

The National Oceanic and Atmospheric Administration (NOAA) provides a Community Resilience Index to calculate a coastal community's resilience score but does not include a process to develop and prioritize mitigation actions. The US Army Corps of Engineers adapted NOAA's index to provide a system for assessing the resilience of coastal areas and prioritizing projects, but the method is focused only on coastal areas. The National Institute of Standards and Technology (NIST) Community Resilience Planning Guide provides a six-step process to help communities set priorities and allocate resources to manage risks for their prevailing hazards [61]. This is similar to the method outlined here, though it lacks the tool to operationalize the process with automated hazard data. The US Army Environmental Command is developing a Military Installation Resilience Assessment to assess hazards to US Army installations, conduct scenario analysis, and assess the cost-effectiveness of potential solutions [62]. The framework is intended to be an operational tool to guide resilience assessments of Army installations, but the model is still in the conceptual phase. The Environmental Protection Agency (EPA) provides a multi-sector approach to evaluating urban resilience to climate change [63]. This method is targeted at local and state planners rather than entities like bases within communities. Beyond urban areas, the EPA Climate Ready Estuaries program also provides a workbook for developing risk-based adaptation plans [64]. The methodology is similar to the one presented here, in that it is a stakeholder driven approach that results in prioritized action items. However, it is targeted at natural resource system managers and focuses on larger scale systems like watersheds rather than specific sites. Additionally, it lacks geospatial analysis integration.

The Department of Energy (DOE) national laboratories have also partnered with federal agencies to develop resilience assessment methodologies. For example, Argonne National Laboratory worked with DHS to develop a resilience index that allows comparison of resilience between facilities [65]. Sandia National Laboratory uses a performance-based resilience metric and GIS methods to analyze how to improve access to infrastructure services across cities after a major disruption using a system of resilience nodes [66]. More recently, the DOE's Federal Energy Management Program (FEMP) has worked with NREL and the Pacific Northwest National Laboratory to create a risk-informed approach to resilience planning to enhance the sustainment of critical energy and water loads to sustain a site's mission. FEMP's Technical Resilience Navigator (TRN) guides federal agency staff through the resilience planning process at the site-level to identify baseline conditions, risks to the site, and identify solutions that can be prioritized for implementation.

Larkin et al. note that because federal agencies are diverse and specialized, national resilience depends on each agency implementing a resilience program that anticipates critical service-specific vulnerabilities and fosters recovery and adaptation to new hazards. Of the methodologies summarized by Larkin, four of the seven primarily address coastal resilience, rather than a broad set of natural and man-made hazards as does our methodology. Furthermore, many of the resilience assessment efforts reviewed only provide assessments to help communities understand where weaknesses exist, but do not offer concrete solutions for improving resilience. Finally, Larkin shows that most assessments focus on community infrastructure and do not rigorously assess electrical, water, wastewater, or telecommunication systems. Therefore, our method builds on the existing literature by providing an all-hazards approach that assesses energy, water, transportation, and communication systems and provides concrete solutions for improving resilience.

Working with the U.S. Air Force Civil Engineering Center and three Air Force bases, the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) developed a replicable energy resilience assessment methodology and investment decision tool to: (1) identify and score hazards and vulnerabilities at the site level (e.g., a building, campus, or base); (2) analyze risks to energy – and in some cases, water - infrastructure; and (3) identify and prioritize energy resilience investments. The methodology and tool address many of the gaps identified in the literature by combining a bottom-up, all-hazards assessment methodology with GIS mapping capabilities to provide an innovative, dynamic tool for identifying and prioritizing actionable solutions. By incorporating a stakeholder engagement process, this method builds resilience capacity in the base community for more enduring impact (i.e., raising awareness of vulnerabilities and potential solutions). Probabilistic forecasting is combined with an iterative approach for continuously updating and reassessing risks to address temporal dynamism and uncertainty. Relationships among systems are modeled and visualized to estimate the effectiveness of resilience actions across multiple interdependent systems. The intention is to create a method and tool to inform financial priorities through cost-difficulty-impact tradeoffs. GIS visualization and action plans enable effective communication of risks and help prioritize mitigation actions for implementation.

The methodology is demonstrated and validated through a case study at Tyndall Air Force Base (AFB). The base located near Panama City, Florida, is home to several critical Air Force missions, including pilot training, air sovereignty and defense, weapon system evaluation, and civil engineering. The assessment focuses on risks to Tyndall AFB's primary missions, infrastructure, and population, as well as risks to infrastructure and population in Bay County, which surrounds the base. Because many people that work on base live in the surrounding county and commute to work, the resilience of the base is closely tied to the resilience of the surrounding community. While the methodology was demonstrated at one specific Air Force base, it can be used more broadly for a portfolio level assessment when scaled across other bases, to understand the risks to an entire portfolio.

The initial resilience assessment was completed two months before Hurricane Michael - a Category 5 hurricane - hit the base. This unfortunate event provided a unique opportunity to review the resilience assessment after the storm and evaluate whether the methodology had effectively identified hazards, vulnerabilities, risks, and mitigation strategies. It is often difficult to validate resilience assessment methodologies through pre- and post-event comparison because extreme events are, by definition, rare. While there are several examples in the literature of studies that applied resilience assessment methodologies after a disaster to see what their model would have predicted if they had been applied pre-disaster [18,23,30,42,45,48,67], it is unusual to have the opportunity to validate a method through both a pre-disaster and post-disaster assessment.

Therefore, the main contributions of this research are: (1) an improved resilience methodology and tool that addresses shortcomings of existing resilience assessment tools by incorporating stakeholder processes, cross-scale relationships, temporal dynamism, and a clear action plan; and (2) validation of the approach through comparison of pre- and post-event assessment results. The following sections describe

Fig. 2. Resilience assessment methodology.

the assessment methodology and its application at Tyndall AFB; compare the pre- and post-hurricane assessment results to validate the methodology; and discuss opportunities for improvements to the methodology and future research.

2. Methodology

The resilience assessment methodology used in this study [68] starts with assessing baseline conditions; then identifying and scoring hazards and vulnerabilities based on likelihood of occurrence and potential impact; analyzing risks; identifying and prioritizing mitigation actions based on cost, difficulty, and impact; creating an action plan; and, finally, implementing solutions (see Fig. 2). Each step is described in more detail below. Typically, the method is completed sequentially, and then revisited and updated periodically. Resilience planning is an iterative process and is intended to be cyclical, evaluating how conditions have changed and assessing the performance of the resilience solutions implemented previously.

2.1. Assess baseline conditions

Establishing a baseline includes understanding the existing conditions to determine the ability of the site to respond and adapt under different operational conditions if a disruption were to occur. Baseline assessments are intended to identify the assets (property, people, information, criticality of operations) that need to be protected. The baseline assessment includes stakeholder interviews, data collection and a literature review of emergency plans, maps and geographic data, utility information and historical data relating to disasters, extreme temperatures, and grid outages. For example, Tyndall AFB provided base planning documents including contingency response plans, base development plans, GIS data on infrastructure types and locations, and base electrical plans. The county supplied emergency plans and county assessments of local hazards. Finally, the utilities provided information on their outages and contingency plans. Tyndall AFB and external stakeholders aided the assessment team in understanding environmental risks and criticality of facilities and missions. This allowed for detailed understanding of both hazards and impacts to the base and surrounding

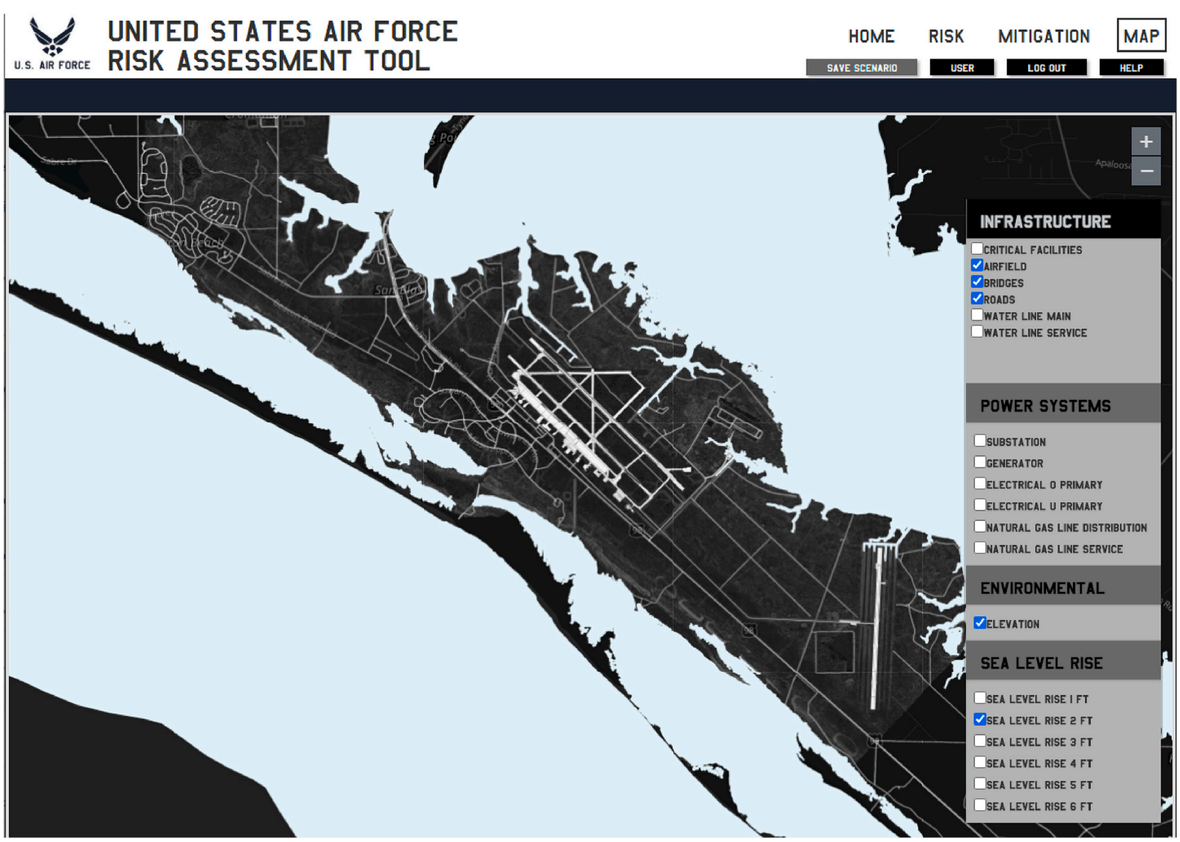

Fig. 3. GIS data on site infrastructure is overlaid with topographical data in the risk assessment tool to help users identify potential vulnerabilities.

area.

The baseline data on electrical and natural gas line locations, telecommunications networks, and backup generation is displayed in the risk assessment tool and overlaid with topography data like floodplains, wetlands, and elevation, to help users determine where vulnerabilities may exist (see Fig. 3).

2.2. Identifying and scoring hazards and vulnerabilities

After establishing the baseline, potential hazards and vulnerabilities are identified and scored to assess the highest risks to the site or community.

2.2.1. Hazards

Hazards and threats expose a vulnerability or damage, destroy, or disrupt an asset. The terms hazards and threats may be used interchangeably although some sources consider threats a sub-category of hazards that are specifically human-caused incidents. This paper uses the broader concept of hazards to include human-related threats.

Hazards are typically identified through literature reviews, state hazard assessments, stakeholder engagement, data mining, and relying on expert knowledge. Anything that can expose a vulnerability, either intentionally or accidentally, or that can damage, destroy, or disrupt an asset is considered a hazard. Hazards are natural, technological, or adversarial threats typically not within the site's control—such as wildfires, hurricanes, storm surges, or cyberattacks. Known or predicted hazards must be identified to understand the potential impacts to the site, and, eventually, the potential mitigation efforts. For example, hazards at Tyndall AFB were identified through review of hazard assessments relevant to northwest Florida. These included reports from the Florida Climate Change Center, the Southern Climate Impacts Planning Program, the National Aeronautics and Space Administration (NASA), and National Oceanographic and Atmospheric Administration (NOAA). NREL used the American Society of Civil Engineers (ASCE) 7 Hazard tool [69] to assess hazards to the built environment on Tyndall AFB. These resources were combined to geographically display hazards and to determine the likelihood of hazards occurring at Tyndall AFB.

For natural hazards, the scores are often assigned using a combination of documented natural hazards, climate projections, and professional judgement based on the likelihood of occurrence assessed from the quality and consistency of data and the degree of agreement among different sources. For non-natural-hazards, scores are assigned based on current understanding of conditions from information collected during stakeholder interviews. The scoring used in this assessment is based on a 1–10 scale, with 1 being least likely and 10 being most likely. Assessments can also be done with a smaller or more qualitative scale, such as low/medium/high.

Non-natural hazards were also noted by Tyndall AFB personnel. The likelihood of such events as political unrest, electromagnetic pulses, and rogue actions changes frequently, and scoring for these types of events was done in concert with base security teams to most accurately assess the hazards.

2.2.2. Vulnerabilities

Vulnerabilities are weaknesses within infrastructure, systems, or processes that can be modified and mitigated to either prevent a disruption from occurring or lessen the impact of a disruption. A vulnerability assessment evaluates the potential vulnerability of an asset against a broad range of identified hazards. Vulnerabilities include physical weaknesses like single points of failure or lack of back-up for electrical, cyber, water, communication, and transportation systems. Vulnerabilities also include natural weaknesses like flood- or fire-prone locations and human limitations like overworked or undertrained employees. Vulnerabilities are identified through expert elicitation in stakeholder interviews, as well as through reviews of planning documents, a common technique in resilience assessment methodologies [28,70]. For example, at Tyndall AFB, the team interviewed 54 stakeholders including the base vice commander, mission owners, the site energy manager, the site electrical engineer, the water program manager, the wastewater treatment plant manager, generator testing and maintenance staff, communications operations staff, site emergency management personnel, GIS staff, the real property manager, and transportation managers. Additionally, the team met with electric, water, and gas utilities that support the base and with community leaders from the county emergency management office and county chamber of commerce. The team also reviewed planning documents such as the emergency management plan, continuity of operations plan, community and site development plans, memorandums of understanding between the site and community, and building codes. Finally, the team reviewed after-action reports from previous events to understand historic grid outages and their resulting disruptions to utilities and services.

Vulnerability consequence scores are assigned using professional judgement, again drawing from the stakeholder interviews and review of available literature, documents, and reports, based on the extent to which each of these hazards could negatively impact business continuity or the site. Consequences of impact are ranked from low (score = 1) to high (score = 10). Drawing from the 5 R Resilience Framework utilized by the Air Force Civil Engineering Center [71,72], an adaptation of Bruneau's original framework [73], the vulnerability score considers the existing robustness, redundancy, resourcefulness, responsiveness, and recoverability of the system in question, in other words, the degree to which an affected process, system, facility, or personnel would suffer or fail as a result of a disruptive event. Because vulnerability identification and scoring are based on stakeholder expertise, there is potential for an incomplete, inaccurate, or conflicting dataset. To address this, the research team interviewed a wide range of stakeholders from across the base with different experiences and points of view, and validated responses against existing planning or after-action documents where possible. The research team looked for consistent patterns in the stakeholder interviews to determine scoring, and in a few cases where there was not consistency, used a weighted average. Still, the vulnerability process is inherently more subjective, and results should be interpreted with that limitation in mind.

Vulnerability probability scores represent the likelihood that a vulnerability will occur, given a realized hazard. Similar to hazard and vulnerability consequence, the vulnerability probability can be scored on a 1–10 scale, with 1 representing low likelihood and 10 representing high likelihood. Alternately, for this assessment, a more simplified binary 0/1 scale is used, where 0 indicates that a hazard does not result in a given vulnerability, and 1 indicates it does.

Using the risk assessment tool, users can select from prepopulated hazards and vulnerabilities or customize their own and define relationships for which hazards impact a given vulnerability. Vulnerabilities are classified based on the systems they impact, such that the interdependencies between systems can be explored. Geospatial data informs the user's hazard and vulnerability identification and scoring by allowing users to map the location of various types of critical infrastructure and explore how it may be impacted under different hazard scenarios. For example, under certain sea-level rise scenarios, key electrical infrastructure might become submerged, indicating a vulnerability in the electrical system.

2.3. Analyze risks

To evaluate the relationship between hazards and vulnerabilities, a risk matrix is created. Risk is a function of the likelihood of a hazard occurring, the probability of a vulnerability being exposed given the realization of a hazard, and the consequence of the vulnerability, as shown in Equation (1).

$$\text{Risk} = \text{Likelihood of Hazard x Probability of Vulnerability x Consequence of Vulnerability} \tag{1}$$

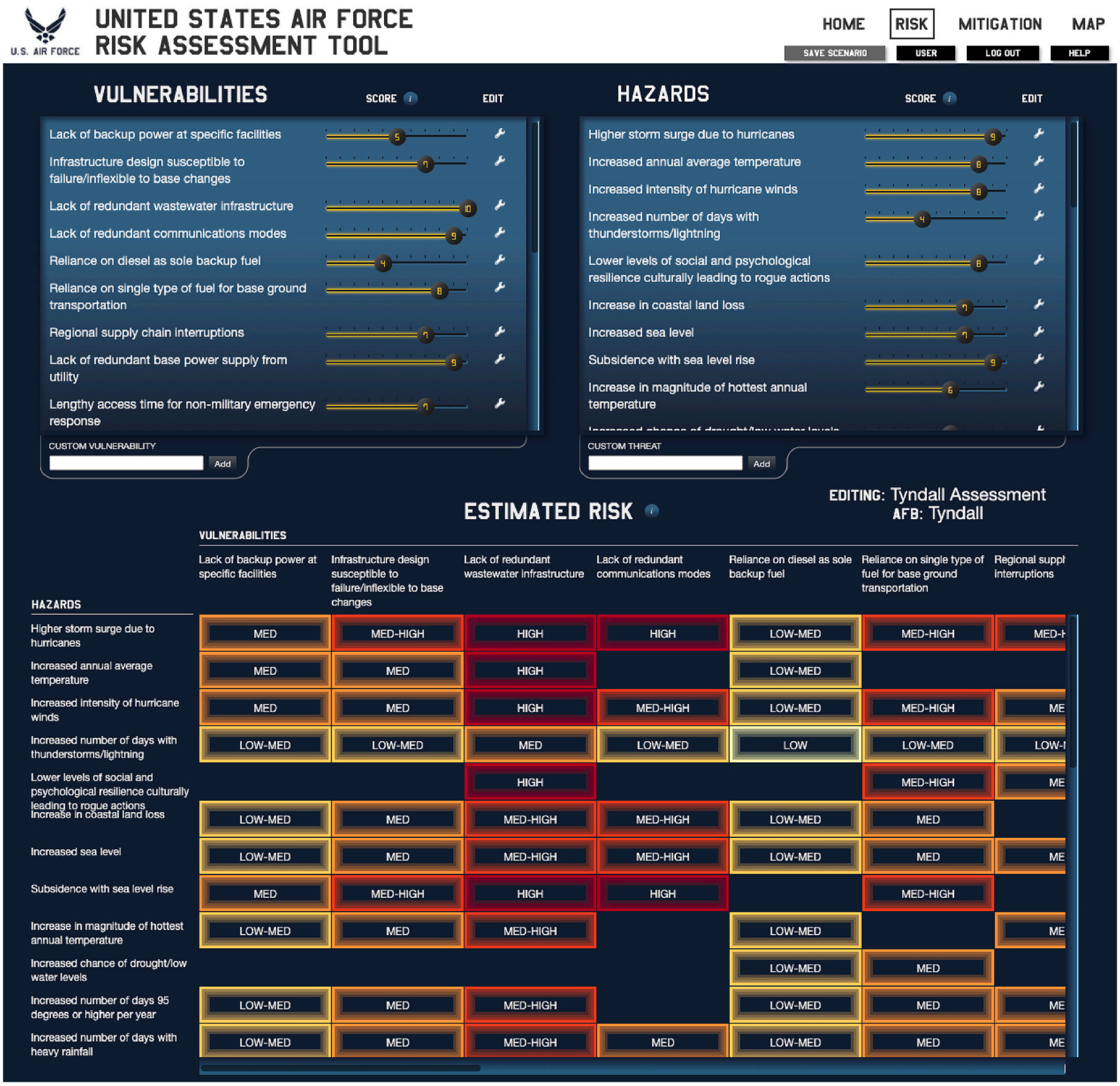

Fig. 4. Risk scores are calculated for each hazard-vulnerability combination in the risk matrix.

A risk score is calculated for each specific hazard-vulnerability combination. For some combinations, the risk score will be zero because there is zero likelihood that the vulnerability will be exposed by a given hazard. For example, at Tyndall AFB, increasing annual temperatures are unlikely to expose the lack of redundant communication nodes, and therefore that hazard-vulnerability combination is scored as 0. On the other hand, high storm surge is likely to cause power outages and expose the lack of backup power at specific facilities, so that hazard-vulnerability combination is rated high risk.

Evaluating risks in this way allows decision makers more insight into potential causes of and vulnerabilities to disruptive events. This can also enable better solutions to be identified as certain vulnerability-hazard combinations emerge. The interactions between these vulnerabilities and hazards are of particular importance to site decision makers and enable more tailored solutions or mitigation actions. For example, at Tyndall AFB the team decided to focus only on risks rated medium or higher, to prioritize limited time and resources on those risks with the highest impact on base resilience.

An example risk matrix is shown in Fig. 4. The tool orders the risks by highest score so that the vulnerability-hazard combinations with the highest risk scores can be prioritized by the user for developing mitigation strategies. The user can also set thresholds so that only risks over a certain score are displayed, allowing the user to focus on the highest risks. The blank areas indicate hazard-vulnerability combinations where the hazard does not expose the given vulnerability.

2.4. Identify and prioritize mitigation strategies

After understanding the risks, the assessment team identifies mitigation options that reduce the exposure or consequence of each vulnerability to respective hazards. Stakeholders that provided input on the vulnerabilities and hazards are a good source for brainstorming the mitigation options as well. Each mitigation strategy is then evaluated based on its potential to reduce the risks to the site or to the community against its difficulty and cost. The score for each mitigation is based on a potential percentage of reduction. In the absence of more granular, site-specific information, low to high reduction scores can be assigned where low = 30%, medium = 50%, and high = 80% risk reduction. The cost

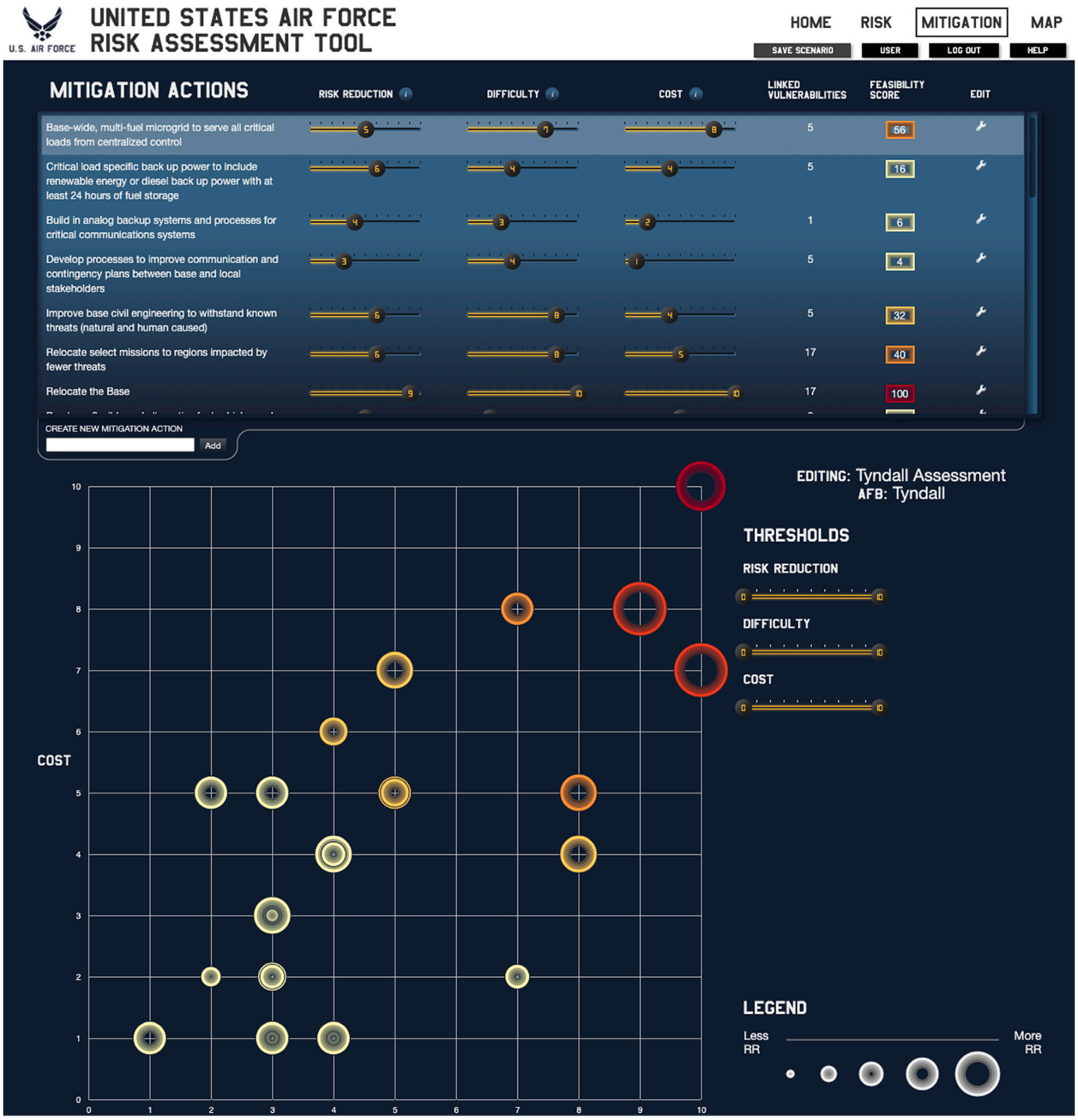

Fig. 5. Mitigations are prioritized based on cost, difficulty, and risk reduction.

and difficulty of each mitigation strategy can be estimated on a low-high (1–10) scale. This process allows mitigation actions to be prioritized based on their cost, difficulty of implementation and ability to reduce risk enabling identification of the highest return actions. For example, at Tyndall AFB decision makers decided to further explore mitigation actions that had a cost and difficulty below 5 and a medium to high risk reduction.

The risk assessment tool provides users a default list of potential mitigation actions to reduce risk, as well as the option to enter their own customized mitigation strategies. The default mitigation actions are mapped to the default vulnerabilities they address as well as cost, difficulty, and estimated risk reduction scores, but these can be changed by the user. For custom mitigation strategies, the user specifies the vulnerabilities that the mitigation addresses, as well as the cost, difficulty, and expected magnitude of risk reduction. Users can then prioritize them based on cost, difficulty, and ability to reduce risk. Different packages of mitigation measures can be evaluated to understand their cumulative impact on risk reduction.

After stepping through the process, the tool presents the results of the assessment in a summary view for concise communication of the greatest risks and most effective mitigation action options. The highest scoring hazards and vulnerabilities, as well as the mitigation options with the highest risk reduction potential, are displayed as shown in Fig. 5. This visualization displays the information in a way that the decision maker can quickly discern the trade-offs between the costs and benefits of a mitigation action. The user can set cost and difficulty thresholds such that only mitigation actions with lower cost and difficulty than the threshold are shown. The user can create different cost/difficulty threshold scenarios and view impacts of the selected portfolio of mitigation actions.

2.5. *Create an action plan and implement solutions*

The final steps in the process are to create an action plan, implement solutions, and measure results. The action plan includes a prioritized list of mitigation strategies, next steps, a timeline, and budget, along with the entity or person responsible for carrying out the activity. The next steps for selected mitigation actions may include a feasibility study (e.g., carry out a detailed study on implementation, costs, and return on investment for creating a microgrid to power critical loads in specific facilities). The risk assessment tool automatically generates an action plan table for all mitigation options that fall below the selected cost and difficulty thresholds. Site personnel can detail the action plan by identifying the point of contact, estimated cost, and timeline for each action. The plan can then be presented to senior leaders for prioritization and funding.

2.6. Iterate on the resilience assessment process

Revisiting the resilience assessment and action plan on a regular basis will help to refine the process and identify where improvements can be or have been made, as well as begin to measure the success of different mitigation strategies to inform the process in future. Reassessing periodically in an iterative approach is also important for continuously updating and reassessing risks, which are likely to evolve over time as hazards and vulnerabilities change with evolving natural hazards, man-made hazards, base infrastructure, and processes. The stakeholder-driven methodology is intended to build institutional capacity for resilience. After participating in the initial assessment, stakeholders continue to contribute to the culture of resilience by applying resilient thinking in their everyday tasks, thus minimizing the level of effort required in future iterations. This increased level of resilient thinking was apparent in the after-storm assessment, thus the second assessment required a significantly reduced level of effort to collect data.

The following section describes the results of the initial resilience assessment at Tyndall AFB, as well as the second iteration when the assessment was updated after Hurricane Michael.

3. Results

The initial resilience assessment was completed in August 2018. On October 10, 2018, Hurricane Michael made landfall centered over Mexico Beach, Florida, 15 miles from Tyndall AFB. At the time of landfall, Hurricane Michael was a Category 5 storm with sustained winds of up to 155 mph and storm surges ranging 9–13 feet. Hurricane Michael was the third most intense storm to make landfall in recorded U. S. history (as characterized by pressure). Additionally, unusually warm water in the Gulf of Mexico—with temperatures ranging from 0.75° to 1.5 °C above average—allowed the storm to grow from a 35-mph tropical depression to a Category 5 hurricane in under 72 h. Hurricane Michael caused significant damage to Tyndall AFB and surrounding communities. Tyndall AFB lost power at different facilities between 6 and 8 days.

This unfortunate event provided a unique opportunity to update the existing vulnerability assessment and validate the methodology used. This section describes the results of the pre-and post-assessments and evaluates how effectively the methodology identified hazards and vulnerabilities realized in Hurricane Michael. While the base did not have time to implement the recommended mitigation strategies before the storm, we analyzed whether the mitigations recommended through the resilience assessment may have reduced the impacts of the storm and identified additional mitigation actions that could further augment resilience. A subset of mission owners and key stakeholders provided input through the stakeholder interview process for the modifications after Hurricane Michael occurred.

3.1. Hazards

Using the methodology described above, natural hazards were identified and scored in the original assessment through a review of hazard assessments and climate projections relevant to northwest Florida, while non-natural hazards were identified and scored with base security expert input. Most hazard scores remained unchanged in the post-assessment, but some were updated by the post-assessment team (the project lead, assessment lead, and Tyndall AFB resilience subject matter expert) based on altered conditions at Tyndall AFB after the storm. These are shown in Table 1. Of note, the extent of tree blowdown on Tyndall AFB and in the surrounding communities caused increases in the likelihood of hazards related to temperature, flooding, coastal land loss, wildfire, relative humidity, and heat index. Trees lower surface and air temperatures by providing shade and through evapotranspiration. They reduce humidity by reducing the availability of surface water for evaporation. Their roots soak up water and help keep soil in place to reduce erosion and flooding and anchor topsoil. Without trees, rain runs off soil and into rivers and streams, clogging riverbeds, raising the water level, and causing erosion. Dead trees are also a source of fuel for

Table 1
Updated hazards and likelihood scores (changes in bold with old score in parentheses).

Hazard	Update	Updated Score
Higher storm surge due to hurricanes	None	9
Increased local annual average temperature	Increase due to localized heat island effect after tree blowdown	**(8) 9**
Lower levels of social and psychological resilience culturally leading to rogue actions	Increase due to stress from housing shortages and health impacts	**(8) 9**
Increased intensity of hurricane winds	None	8
Increased number of days with thunderstorms/lightning	None	8
Increase in coastal land loss	Increase due to loss of trees/ vegetation, which increases risk of erosion and land loss.	**(7) 8**
Wildfire	Add due to increased fuel from downed trees	**8**
Increased sea level	None	7
Subsidence with sea level rise	None	7
Increase in magnitude of hottest annual temperature	Increase due to fewer trees	**(6) 7**
Increased number of days with heat index of 95°F or higher per year	Increase due to fewer trees	**(6) 7**
Increase in relative humidity	Increase due to fewer trees	**(5) 7**
Increased number of days with heavy rainfall	None	6
Increased amount of precipitation on days with precipitation	None	6
Reductions in programs or budgets that support protection and cultural resilience	None	6
Decreased annual rainfall	None	5
Increased annual average precipitation	None	5
Increased annual average rainfall	None	5
Increased number of days with high winds	None	5
Flooding	Add due to decreased water uptake from fewer trees	**5**
Increased chance of drought/low water levels	Reduce due to fewer trees soaking up water	**(6) 4**
Decrease in relative humidity	Reduce due to fewer trees	**(5) 4**
Disruptions due to electromagnetic pulses, GMP/solar flares	None	4
Increase in magnitude of lowest annual temperature	None	4
Increase in number of tornados	None	4
Increased average wind speed	None	4
Reduced water availability	None	4
Political threats	None	3
Saltwater inundation of backup wells	**Add due to water table changes**	**3**
Increased number of days with freezing temperatures	None	2
Earthquakes	None	1
Sinkholes	None	1

Table 2
Updated vulnerabilities and impact scores (changes in bold with old score in parentheses).

Vulnerability	Update	Updated Score
Lack of backup power at specific facilities	None	10
Infrastructure design susceptible to failure and inflexible to base changes	None	10
Lack of redundant wastewater infrastructure	None	10
Lack of redundant communications modes	Increase because significant failure during this storm	**(9) 10**
Community infrastructure failure impacts the base	Increase because multiple failed community infrastructure and support networks during this storm	**(7) 9**
Reliance on diesel as sole backup fuel	None	8
Reliance on single type of fuel for ground transportation	None	8
Regional supply chain interruptions	None	8
Lack of planning for sheltering in place	Increase because failure of the Emergency Operations Center was a significant issue in this storm	**(7) 8**
Critical mission workforce lives off-site with single point of access	None	7
Lack of redundant water supply	None	7
Base is vulnerable to insider threat from number of contractors coming onto base with limited oversight	Add due to increased volume of contractors, the reduced ability to monitor all contracting work, and the limited resources to control the base perimeter.	**7**
Lack of redundant base power supply from utility	Decrease because two lines across bridge are now hardened, though there is still not an alternative feed.	**(7) 6**
Lengthy access time for emergency response	Decrease because not an issue in this storm	**(7) 6**
Physical vulnerabilities due to base geography	None	6
Lack of granular data on energy consumption/needs	None	6
Lack of formal agreements for emergency response and clear roles with surrounding community	Increase because was a challenge during this storm	**(4) 6**
Reduced patrols by local civilian police boats have increased perimeter vulnerabilities	Add due to civilian police boats relocation after the storm; now have a reduced presence near base.	**5**
Lack of housing and affordable housing	Add due to inability to bring families back to the base	**4**
Increased visibility into base due to downed trees	Add due to increased visibility for security teams around the base perimeter. Further study may be required.	**3**
Lack of coordination and communication between utilities serving the base	Decrease because utilities supported each other in getting base back online during this storm.	**(3) 2**

wildfires. This phenomenon has not been well-characterized enough to understand how long the increased hazards will persist. As such, regular monitoring of groundwater levels, coastal erosion, wildfire conditions, and humidity may be required to fully understand the nature of the changed hazard.

Additionally, hazard levels associated with social and psychological resilience have increased due to lingering effects of the hurricane on the surrounding community where most base personnel previously lived. Stresses include increased home prices, inability to relocate families to

Table 3
Updated mitigation actions and scores (changes in bold with old score in parentheses).

Mitigation Action	Update	Difficulty	Cost	Risk Reduction
Base-wide microgrid to serve all critical loads	None	7	8	Med
Critical load-specific backup power	None	4	4	High
Build in analog backup communication systems for critical buildings	More extensive/costly updates required. Storm showed high impact of communications.	3	**(2) 4**	**(Med) High**
Develop agreement to improve communication and contingency plans for internal and external stakeholders	None	4	1	Med
Improve base civil engineering (e.g., drainage, elevation of infrastructure, underground lines)	Easier now due to rebuild	**(8) 5**	4	High
Relocate select missions	None	8	5	High
Relocate the base	None	10	10	High
Purchase flexible and alternative fuel vehicles, including relevant infrastructure to support fuel diversification	None	2	5	Med
Duplicate mission capability and transfer process elsewhere for redundancy	None	4	4	Med
Retool operation to use jet fuel as backup supply for generators	None	1	1	Med
Install submeters and advanced metering for greater granularity of energy and water needs and management	Easier now due to rebuild	**(3) 2**	3	Low
Improve water infrastructure: add lines and storage	None	3	3	Med
Improve wastewater infrastructure: add additional lines and treatment and reducing infiltration	None	3	5	Med
Develop policies and procedures for monitoring and mitigating outdoor worker heat stress and other hazards	Increased impact with rising temperatures from tree loss.	3	1	**(Med) Med-High**
Temporary relocation of critical missions	None	3	2	Med
Develop strong working relationship with county with regular chains of communication	Easier due to regular county recovery team meetings	**(4) 2**	1	Med
		(3) 1	1	**(Low-Med) Low**

(*continued on next page*)

Table 3 (*continued*)

Mitigation Action	Update	Difficulty	Cost	Risk Reduction
Improve site access process for critical contractors	Site access was not problematic during this storm.			
Relocate critical staff to live on base	None	4	6	Med
Add redundant power line to the base	Some improvements already made	**(5) 3**	5	Med
Incorporate resilient design into new development	Easier now due to rebuild	**(3) 1**	3	High
Work with community to ensure resilience of base supporting community infrastructure	Regular base-county recovery team meetings reduce difficulty/ cost. Failed community infrastructure had large impact on base.	**(2) 1**	**(2) 1**	**(Low) Med**
Diversify supply chains	None	7	2	Med
Duplicate EOC operations in multiple buildings	Added due to failure in EOC	**2**	**2**	**Med**
Physically protect communications nodes in stand-alone buildings built to new storm-resistant codes	Added due to antenna failure	**3**	**6**	**High**
Consider marina facility to access base if bridge is closed	Added due to bridge closure	**4**	**6**	**Med**
Clear downed trees and build fire breaks	Added due to downed trees	**3**	**5**	**Med**
Start reforestation to reduce heat island effects, mitigate excess water and buffer winds	Added due to downed trees	**3**	**6**	**Med**
Build additional cooling facilities and budget for increased cooling costs.	Added due to downed trees	**3**	**3**	**Low**
Increase remote monitoring of base perimeter through automated technology	Added due to downed trees	**3**	**5**	**Med**

Tyndall AFB/Bay County, increased cost of living, and reduction in services, including school options for children of base personnel.

3.2. Vulnerabilities

Using the methodology described above, vulnerabilities were identified and scored in the original assessment through stakeholder interviews and review of planning documents. Like hazard scores, most vulnerability scores remained unchanged in the post-assessment; however, some were updated to reflect lessons learned and post-hurricane conditions on Tyndall AFB. Notably, backup power options were adequate during and immediately after the storm; however, reliance on a single type of fuel for backup generators and for transportation could still cause failures during future events, as shown in studies on humanitarian supply chains [74,75]. Some systems did not perform well during the storm, including physical security, communications, and housing. Additionally, new vulnerabilities were exposed as the ability to maintain site security was reduced. Finally, some changes in vulnerability are not yet known. The significant number of downed trees creates a greater line of sight into the base, which could increase the possibility of bad actor-related vulnerabilities; however, the downed trees also allow site security personnel a greater line of sight out of the base, which could reduce vulnerability at the fence line.

Table 2 describes the new and updated scores, as well as the justification for the score change.

3.3. Mitigation

Using the methodology described above, mitigation strategies were identified and prioritized in the original assessment by the research team with input from the base stakeholders through stakeholder interviews and review of planning documents. In the post-assessment, mitigation strategies were updated to reflect the impacts and lessons learned from Hurricane Michael. New mitigation options were added to address new or increased hazards and vulnerabilities around communications, sheltering in place, base access, utility coordination, wildfire, increased temperatures, and flooding. The difficulty scores of several mitigation strategies were reduced because they will be easier to implement during the rebuilding process. The risk reduction potentials of several mitigation actions were increased to reflect their ability to further reduce risk of vulnerabilities that were increased in the reassessment. These included mitigation options associated with backup communications systems, outdoor worker heat stress mitigation, and increased resilience of community infrastructure. Several new mitigation strategies were also added to reflect new vulnerabilities that were exposed or created as a result of the storm. Notably, several vulnerabilities related to site security and access were created or amplified. These vulnerabilities can be largely assessed and reduced through increased use of remote monitoring technologies, such as motion-activated video cameras and shot detection sound monitoring networks. Like other mitigation strategies, it may be most expedient to deploy these strategies during the rebuilding phase.

Table 3 describes the new and updated mitigation strategy scores, as well as the justification for the score change.

4. Discussion

Hurricane Michael provided a unique opportunity to validate the resilience assessment process. The review of the resilience assessment found that the process was effective in identifying potential hazards and vulnerabilities. Hazards and their likelihood scores were primarily based on long-term climate data and remained largely unchanged in the reassessment, except for where the storm altered local conditions going forward. Three new hazards were identified, and 28% of the likelihood scores were slightly updated by one to two points based on altered conditions from the storm (downed trees and reduced psychological resilience).

Vulnerabilities also remained largely unchanged, with only one new vulnerability identified in the reassessment (housing shortages created by the hurricane damage). About 40% of vulnerability scores were slightly updated by one to two points after the storm revealed vulnerabilities that were more or less impactful than previously assessed. The larger number of vulnerability score updates may be due to the more subjective scoring process of vulnerability impact, which is largely based on interviews and expert judgment, rather than long-term data sets. The impact of vulnerabilities will vary depending on the hazard event, as well as changing conditions of the base, so it will be important to reassess vulnerabilities periodically going forward as the base rebuilds.

New mitigation actions were developed in response to new hazards and vulnerabilities. New post-storm conditions, combined with lessons learned during the storm, resulted in identifying six new mitigation actions. The scores of existing mitigation actions changed slightly, with 20% of the existing mitigation scores updated by one to three points, largely due to the base's rebuilding plans, which impacted the cost and difficulty of some mitigation strategies (primarily reducing difficulty, as

Table 4
Changes in hazard, vulnerability, and mitigation identification.

	Original Assessment	Post-Storm Reassessment	Percent Increase
Hazards	29	32	10%
Vulnerabilities	18	22	15%
Mitigations	22	30	36%

many mitigation actions can be incorporated into existing rebuild plans). Because the storm happened before Tyndall AFB could implement any of the recommended mitigation actions, the effectiveness of the recommended mitigation actions in reducing vulnerabilities could not be quantified; however, many of the mitigation strategies identified likely would have increased the base's resilience during Hurricane Michael. For example, having backup analog communication channels could have facilitated better coordination with the community and faster recovery when the VoIP and cellular phones failed.

Table 4 and Table 5 summarize the validation findings, measured by changes to the number of hazards, vulnerabilities, and mitigation actions identified pre- and post-storm, as well as changes in scores.

Based on the relatively small number of additional hazards, vulnerabilities, and mitigation strategies identified, and the small degree of changes to scores, the resilience assessment process was deemed to be effective in assessing risk and identifying comprehensive actions to increase site energy resilience.

Compared to other validation methods in the literature, this method is somewhat unique in that it is validated empirically based on an actual event. Among quantitative methods, few indices are empirically validated using observed disaster impacts because an event must occur before a method can be tested by experience. Asadzadeh et al. (2017) note that disaster resilience measures suffer from a lack of validation, and more work is needed to examine how reliably a framework measures the concept of disaster resilience in an empirical application [76]. Bakkensen et al. (2016) empirically validate five of the top U.S. disaster indices, including three resilience indices and two vulnerability indices [77]. They find that most indices perform as predicted in explaining damages, but fewer explain fatalities or disaster declarations as expected by theory. This highlights the need for more empirical validation, because even indices that are well substantiated by theory may not perform as expected in reality.

Among qualitative resilience assessment methods, in the absence of an actual event occurring, often the process is validated rather than the outcomes. This includes ensuring the process adheres to best practices in probability elicitation, judgmental forecasting, and the Delphi (consensus-based) approach to eliciting expert judgment [28]. A second way to validate judgments is to compare them to the actual experience in previous events. However, the value of this approach is limited because vulnerabilities are strongly depending on local conditions and event characteristics. A third method is using proxy data to validate methods. For example, social vulnerability indices have been validated with proxy data including mortality, built environment damage, economic losses, human migration, residential mail delivery, and household surveys, with mixed results [78]. Kontokosta and Malik (2018) use service requests before, during, and after Hurricane Sandy in as a proxy for measuring neighborhood activity and recovery time [79].

While validation methods are imperfect, ultimately the purpose of a resilience assessment is not to predict the exact consequences of a disaster, but rather to help decision makers think through hazards and vulnerabilities, prioritize mitigation strategies, and develop plans to increase resilience. In this sense, the method presented here contributes an empirically validated methodology that may be useful to others in assessing base, campus, and community resilience.

5. Conclusion and future work

The resilience work described in this paper is intended to be a replicable assessment methodology and initial investment decision tool to identify and score hazards and vulnerabilities, analyze energy risks, assist in identifying interdependencies among infrastructure resources, and identify and prioritize energy resilience investments. Several improvements in resilience assessment methodologies were demonstrated by combining a bottom-up, all-hazards assessment approach with GIS mapping capabilities to provide a dynamic tool for identifying and prioritizing actionable solutions. By incorporating a stakeholder engagement process, this method builds resilience capacity in communities where it is applied for more enduring impact. Probabilistic forecasting was combined with an iterative approach for continuously updating and reassessing risks to address temporal dynamism and uncertainty, while also creating a dynamic process to adjust for changing conditions or improvements. Relationships among systems are modeled and visualized to estimate the effectiveness of resilience actions across multiple, interdependent systems, and inform financial priorities through cost-difficulty-impact trade-offs. GIS visualization and action plans enable effective communication of risks, and implementation of prioritized mitigation strategies.

The methodology was validated by comparing the vulnerabilities, hazards, and mitigation actions identified before the storm to those realized afterwards. Based on the relatively small number of additional hazards, vulnerabilities, and mitigation strategies identified, and the small degree of changes to scores, the resilience assessment process was effective in assessing risk and identifying comprehensive actions to increase site energy resilience.

The reassessment process allowed the addition of more detail to existing mitigation actions, resulting in more specific, targeted actions. It also highlighted an opportunity to enhance the methodology through greater consideration of the interdependencies between the energy system and related systems. While the method is focused on energy, many of the highest vulnerabilities in this storm were not energy system vulnerabilities but impacted the recovery of the energy system and the base.

The results also show that it is important to continually update the risk assessment as external and internal conditions change. Lessons learned during actual events or exercises can be used to identify additional mitigation strategies that may be applicable both at this site and more broadly. Still, it is important not to focus on a single event. Large storms represent a specific hazard, and it is possible that future hazards may expose different vulnerabilities than this hurricane. As such, an all-hazards approach (as used in this assessment) is recommended.

This work leverages previous resilience risk assessment

Table 5
Changes in Scoring.

	Number of Scores in Original Assessment	Number of Scores Changed Post-Storm	Percentage of Scores Changed	Average Point Change in Score (Absolute Value)	Number of Increased Scores	Number of Decreased Scores
Hazards	29	8	28%	1.25	6	2
Vulnerabilities	18	7	39%	1.29	4	3
Mitigations						
Difficulty	22	7	32%	1.9	0	7
Cost	22	2	9%	1.5	1	1
Risk	22	4	18%	1.25	3	1

methodologies and advances the practice through the development of a customizable tool that can be employed at the site level and also used for standardization and comparison across a portfolio of sites. Additional development of the methodology and tool is planned to further refine the process and outcomes. The methodology is also being adapted to non-DOD facilities and communities for further validation. Future work will concentrate on incorporating the value of resilience and economic impact into the model to inform investment and monetization decisions. This next step is especially critical for sites that need to demonstrate that investments have a positive return. Additional visualization work is also planned to model the interdependencies and impacts between different layers, for example, the impact of an electrical outage on the water or communication systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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