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Vulnerability Assessments for Evaluating the Sensitivity of Infrastructure to Environmental Change

Eliza J. Oldach and Priya Shukla
Department of Environmental Science and Policy, University of California, Davis, CA, USA

Definitions

Vulnerability Assessment (VA) An analysis used to identify, quantify, and prioritize the vulnerabilities of a given system.

Adaptive Capacity The ability of a system to change to accommodate social and environmental perturbations.

Exposure The degree to which a system experiences perturbations associated with broader environmental or social change.

Infrastructure The basic physical and organizational structures that underpin the operations of a community or enterprise.

Resilience A system's ability to absorb a disturbance without altering its core function or identity.

Sensitivity The degree to which a system is modified or affected by social or environmental perturbations.

Vulnerability The susceptibility of a system to harm resulting from societal or environmental change; based on the system's exposure, sensitivity, and adaptive capacity (IPCC 2014).

Infrastructure and industry have the potential to empower developing and developed economies to prosper by providing the communal facilities, services, and economic opportunities that improve how communities function. However, global climate change threatens the establishment and longevity of beneficial infrastructure and industry, while exacerbating the impacts of harmful arrangements. Here we describe how vulnerability assessments (VAs) can be employed to understand the complex interactions of infrastructure and industry with social and biophysical conditions in a changing world.

Introduction to Vulnerability Assessments

The nation of Jordan is facing severe, and increasing, water scarcity. Climate change is driving decreases in annual precipitation levels, allowing

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saltwater intrusion into aquifers and increasing rates of freshwater evaporation from reservoirs. Because Jordan is reliant on agriculture and water-intensive industries for livelihoods and food production (Hadadin et al. 2010), an estimated 87% of Jordan's GDP will be impacted by water stress (World Bank 2017). Beyond this, global social factors like instability and migration are creating new and unplanned areas of water requirement. Water scarcity drives considerable threats to human well-being through food insecurity, thirst, and disease.

To meet its water needs, Jordan is developing new dams and water transport systems to capture surface water and draw from groundwater aquifers. Jordan is also relying increasingly on wastewater recycling innovations to supply this critical resource (World Bank 2017). Beyond infrastructure changes, Jordan is entering complex water diplomacy negotiations with Israel and Palestine to share and desalinate water from the Red Sea (Eran et al. 2018). However, even with such innovative responses, Jordan remains the fourth most water-scarce country in the world. Water stress for Jordan, and for the broader region comprising the Middle East and North Africa, is only expected to worsen as climate change continues (World Bank 2017). The physical and social implications of water scarcity stretch across the nation and region. The severity of risks and the success of adapting to this challenge will impact human well-being, production of critical goods, and political stability (Fig. 1).

As the case in Jordan reveals, the interplay of global climate and social change with local infrastructure and industry creates a complex web of interactions and feedbacks. Vulnerability has a crucial role to play in tracing these complex

Vulnerability Assessments for Evaluating the Sensitivity of Infrastructure to Environmental Change, Fig. 1 Aqaba, Jordan, where the desalination plant shared between Jordan, Palestine, and Israel resides (Public Domain). (Beivushtang 2005. Photo from: Wikimedia Commons, https://creativecommons.org/licenses/by-sa/3.0/deed.en) interactions and providing insight into opportunities for adaptive response. The UN Sustainable Development Goals (UNSDG) seek to achieve a "better and more sustainable future for all" in the face of such extreme global change, and SDG 9 urges the implementation of infrastructure, innovation, and industry to move towards this goal. Vulnerability is a useful framework to enable pursuit of SDG 9 for several broad reasons:

- Vulnerability assessments (VAs) can identify the role of infrastructure and industry in exacerbating risks of climate and social change.

  The risks of climate change to infrastructure are notable: rising sea levels threaten ports and harbors; storm surge damages seaside roads and buildings; heavy precipitation causes inland rivers to flood cities and neighborhoods; and heat waves compromise the integrity of roads, runways, and transport structures (Nicholls and Cazenave 2010; Bhat et al. 2013; Mills and Andrey 2002). Industry is also affected, particularly when it relies on climate-sensitive natural resources or infrastructure.
- VAs can identify the role of infrastructure and industry in mitigating impacts of climate and social change.

  Infrastructure and industry can ameliorate climate change impacts. For example, the creation of climate-durable infrastructure can fulfill critical needs in the face of changing climate. Sustainable industry creates jobs and facilitates economic growth that provides the resources, information, and networks that enable adaptation. VAs encompasses this, documenting the potential for adaptive capacity that mitigates environmental and social disruptions.
- VAs incorporate social and biophysical aspects of climate change vulnerability.

  Socioeconomic inequities compound the stability or instability of climate change effects. Impoverished communities are especially susceptible to the consequences of climate change because they have limited access to durable infrastructure and sustainable industry (USGCRP 2017). Together, these could provide crucial resources for climate change resilience, including secure housing, clean water, maintained livelihoods, food security, and information technology (CC-RAI 2014). In examining social impacts and drivers alongside biophysical impacts and drivers, VAs can shed light on the complexities and opportunities for change within these systems.
- VAs are well-suited to examine the uneven spread of climate change impacts across the world.

  Context-specific layers of ecological condition, social factors, and institutional response play into and affect climate change vulnerability. Interactions between climatic factors, non-climatic factors, and multidimensional inequalities mean that different actors are likely to experience climate change differently, even if they face the same risks (IPCC 2014). For example, Pakistan, like Jordan, is threatened by climate-change-linked water scarcity. However, Pakistan's response to this scarcity is different from Jordan's and is focused on developing federal and provincial policies to regulate water use and train farmers on new irrigation practices (Ahmad et al. 2004; Eran et al. 2018). VAs provide a specific analysis that is critical in responding to the uneven spread of climate change impacts and adaptations.

Overall, VAs provide a tool to analyze these systems, tracing causal factors and identifying priorities for adaptation. In the complex interplay of environmental and social change facing the world at large, and the developing world in particular, VAs are likely to serve an increasingly important role. In this chapter, we offer a general background to the study and assessment of vulnerability.

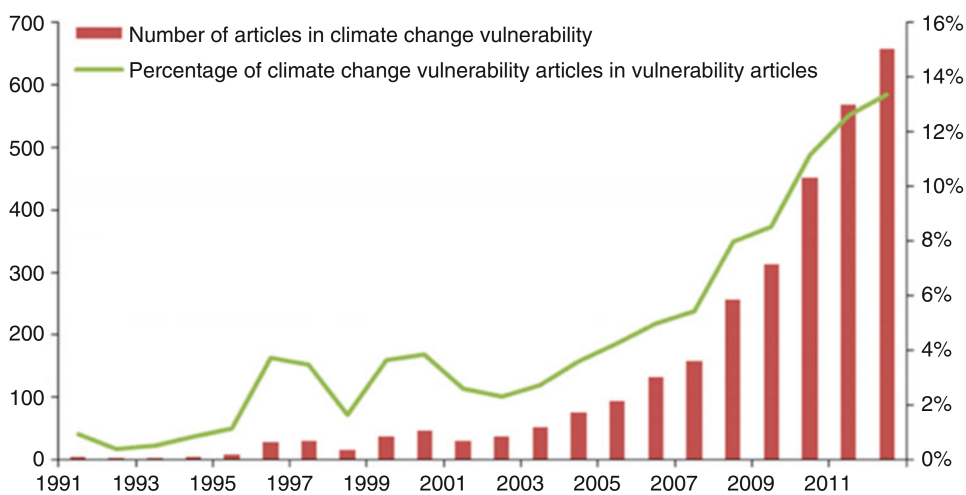
Defining Vulnerability

One of the first steps in a VA is defining vulnerability. Most generally, vulnerability is the susceptibility of a system to being harmed. However, the past several decades have seen a steep rise in the number of publications dealing with this term (Fig. 2, Wang et al. 2014). With this increase in use comes an increase in interpretations; today, vulnerability research stretches from biophysical evaluations to social analyses, and there is still no single definitive interpretation (Ford et al. 2018). Determining the definition used in an assessment is crucial, because it shapes the approach, methodology, and ultimate utility of a VA.

One interpretation of vulnerability has roots in risk and hazard research (Janssen et al. 2006). In this family of assessments, researchers characterize a biophysical stressor related to climate change and calculate its impact on natural systems, sometimes including related social and economic costs. This interpretation is called "outcome vulnerability" or "end-point vulnerability," where vulnerability is conceptualized as a static characteristic of a system and calculated as the difference between impact and adaptation (O'Brien et al. 2004). Broadly, outcome vulnerability assessments are useful for understanding "who" and "what" is vulnerable to climate change (Brugère and De Young 2015).

"Context vulnerability" was developed to better address "why" certain groups are vulnerable. Contextual VAs examine the internal social and political characteristics of a system that temper its response to external stress. In this interpretation, vulnerability is not a static characteristic but a dynamic space defined by political, economic, social, and institutional conditions (Bohle et al. 1994). Human welfare and social processes are central to context vulnerability, and concepts like equity and entitlement (the ability of an individual or group to call on resources) are key factors in determining the system's response to stress (Adger and Kelly 1999). Context vulnerability expands and draws from several different fields, including political ecology, political economy, social-ecological systems, and resilience studies, each of which shifts the emphasis to different driving factors. For example, political ecology and political economy analyses focus on policies and institutions with an eye towards agency and equity among key players. In contrast, social-ecological systems and resilience approaches widen the scope to incorporate feedbacks between social systems and ecosystem dynamics (Barnett and Eakin 2015; Brugère and De Young 2015).

Many efforts have been made to bridge outcome and context vulnerability approaches, resulting in VAs that consider biophysical and social components of a system together (Eakin and Luers 2006). The Intergovernmental Panel on Climate Change's (IPCC) integrative definition of vulnerability has become the predominant one used to design and conduct VAs (IPCC 2014).



Vulnerability Assessments for Evaluating the Sensitivity of Infrastructure to Environmental Change, Fig. 2 Trend in publications in the field of climate change vulnerability (Wang et al. 2014)

According to the IPCC, vulnerability is a function of a system's (1) ***exposure*** – the degree to which it is likely to experience perturbations associated with social and environmental change, (2) ***sensitivity*** – the degree to which it is modified by perturbations it experiences, and (3) ***adaptive capacity*** – its ability to change to accommodate the perturbation (Fig. 3, Turner et al. 2003). Across the diversity of vulnerability definitions in use, these three core aspects are broadly agreed upon (Ford et al. 2018). This interpretation is valuable for its flexibility: each of the components can be adjusted to best reflect the system in question and the breadth of factors influencing vulnerability (IPCC 2014).

The diversity of vulnerability interpretations can be viewed as strength, allowing a single concept to describe a rich array of different climate change considerations. However, this diversity also requires that researchers are careful about choosing a suitable interpretation and are explicit in communicating the capabilities of their approach.

Complementary Concepts

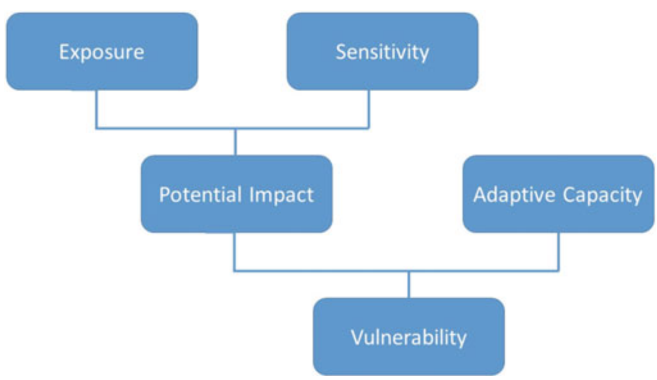
VAs stem from multiple disciplines, allowing them to integrate analogous frameworks that assess how natural and social systems respond to change. Because some of these concepts overlap with the IPCC's widely used interpretation of vulnerability, they can contribute to our understanding of exposure, sensitivity, and adaptive capacity. A few integral frameworks are described below.

Institutional Analysis and Development (IAD) Framework

The IAD framework considers how rules and institutions (formal and informal) shape human behavior and collective action (Ostrom 2011; Klein 2010). IAD is especially valuable when there are conflicting objectives within a community because it examines feedbacks among various actors within a system. In fisheries, for example, the competing goals of catching enough fish to generate income and feed a community while leaving enough fish to allow the population to replenish requires navigating between multiple stakeholders with different moral, social, and institutional principles (Fig. 4, Imperial and Yandle 2007). The IAD framework addresses the friction and harmony among these groups, their relations to broader institutional systems, and how this interplay may determine the fate of an imperiled fish stock. In conjunction with VAs, the IAD framework elucidates complex interactions between actors at different levels of governance and thus sheds light on factors that may influence sensitivity and adaptive capacity (Brugère and De Young 2015).

Sustainable Livelihoods Framework

The Sustainable Livelihoods (SL) framework comprehensively analyzes the factors leading to



Vulnerability Assessments for Evaluating the Sensitivity of Infrastructure to Environmental Change, Fig. 3 IPCC Vulnerability Assessment Framework. (Adapted from Brugère and De Young 2015)

Vulnerability Assessments for Evaluating the Sensitivity of Infrastructure to Environmental Change, Fig. 4 A fisherman operates a one-man boat and prepares to catch fish in Inle Lake, Myanmar. (Baptiste Azais, Unsplash). (Baptiste Azais 2013. Photo from: Unsplash, https://unsplash.com/license)

poverty and preventing access to critical resources (DFID 1999). According to the SL framework, the impact of external environmental or social shocks on internal human, natural, financial, physical, and social forms of capital in a system determine livelihood vulnerability. Improving the accessibility to and sustainable use of necessary resources as well as developing livelihood alternatives may reduce this vulnerability. Ultimately, livelihood vulnerability decreases when household incomes, food security, and access to health and education resources rise (Scoones 1998). These results are dependent upon behavioral and policy changes, providing an opportunity to integrate the IAD framework as well. A VA could be used at any point in the SL framework to analyze how exposure, sensitivity, and adaptive capacity influence the feasibility of desired livelihood outcomes.

Resilience Framework

Like vulnerability, the definition and interpretation of resilience depends on the context within which this framework is implemented. Broadly, resilience is a human or natural system's ability to endure a perturbation without compromising its identity and function (Holling 1973). While vulnerability examines weaknesses within a system, resilience identifies a system's capacity for recovery. The resilience framework aims to analyze the components of resilience – ability to learn, adapt, and reorganize – to develop action items that will help restore or improve resilience-enhancing functions (Folke et al. 2003; Walker et al. 2002). Although the concept of resilience is rooted in natural science, it has since been used to analyze social-ecological systems (Miller et al. 2010). For example, a resilience framework used to analyze the recovery of aquaculture and rice farming operations in Aceh, Indonesia, following the devastating tsunami in 2004 found that the tsunami's impact extended well beyond the area of inundation. This was largely due to the social and economic ramifications associated with land degradation and diversion of labor (Daly et al. 2017). This entanglement of social and environmental consequences exemplifies the close relationship between resilience and vulnerability (Miller et al. 2010). Both frameworks can assess a social-ecological system's capacity for rehabilitation, while the three components of resilience can help inform sensitivity and adaptive capacity measures in a VA.

VA Methodologies

Throughout the VA process, a researcher will face many decision points about methodology, the scale at which the VA should be conducted and implemented, the limitations of the VA, and best practices. Here, those decision points are briefly discussed. Ultimately, a close understanding of the system in question and the needs the VA must meet will determine the best approach.

Methodological Approach

Quantitative

To understand and predict vulnerability, quantitative analysis relies on numerical data concerning environmental, economic, and social conditions. The quantitative approach is closely connected to the outcome vulnerability interpretation and is sometimes termed "top-down" analysis, reflecting the history of external researchers with specialized modeling knowledge conducting analyses and passing "down" solutions to the community-in-question (Brugère and De Young 2015; Mercer et al. 2008).

Foundational tools used to analyze quantitative data in VAs include modeling and statistical downscaling. In modeling, systems are represented through a subset of causal factors used to calculate future conditions; in downscaling, broad patterns of ecological or social change are projected to local effects (UNFCCC 2011). Both of these tools are proofed using statistical analysis, which generates a measure of confidence for model or downscaling findings. Quantitative methods are capable of analyzing complex systems and interactions by incorporating large amounts of data from a variety of indicators. They are particularly useful for analyzing causal relationships and predicting future conditions. However, the benefits of the quantitative approach may be limited in situations lacking the volume and accuracy of data needed to populate models (WHO 2013).

Qualitative

Qualitative analysis relies on non-numerical data to assess the social conditions driving vulnerability. The qualitative approach is closely connected to the SL framework described above (Brugère and De Young 2015). This approach is suitable for collecting data on conditions that can be difficult to quantify, including well-being and equity. In VAs, common qualitative methods include interviews, surveys, field observation, and expert judgment. Qualitative analyses can also forecast future vulnerability conditions, though these predictions tend to operate on a shorter timeframe (WHO 2013).

Participatory

Participatory methods do not follow the conventional dynamics of research. In this approach, stakeholders describe and organize knowledge of their system through their own language, concepts, and frameworks. The researcher, rather than questioning stakeholders to extract knowledge, helps facilitate a process of collaboration and data collection between stakeholders. Sometimes termed "bottom-up," the participatory approach helps build networks between stakeholders, including often-marginalized groups, and actively engages them in the VA and decision-making process (Mercer et al. 2008).

Participatory methods can include a wide variety of activities, including focus groups, priority ranking, mapping, and timeline creation. This method can use and produce both qualitative and quantitative data. Overall, participatory approaches are characterized less by the data-collection activity itself, and more by attitude, behavior, and engagement between facilitators and stakeholders. Different sets of guidelines and best-practices help avoid issues of bias, exploitation, and extensive time requirements (Mercer et al. 2008).

Integrative

Methods are being developed that allow the integration of quantitative and qualitative data collected from a variety of stakeholders to arrive at a more comprehensive VA. Agent-based modeling simulates the actions and interactions between individuals or households in a crafted environment, incorporating both quantitative and qualitative data to understand how overarching patterns arise from individual decisions. Multicriteria decision analysis is a formal modeling approach that incorporates mixed sets of data, weighing social, environmental, technological, and economic factors to guide group decision-making. Scenario or storyline development also incorporates different types of data and potential decision-outcomes to present a variety of futures for comparison and decision-making (WHO 2013). Mapping is also integrative, allowing the visualization of various data sources to illustrate vulnerability and identify areas of greatest concern (Cadag and Gaillard 2012; Brugère and De Young 2015).

Scale

VAs have the capacity to deal with a number of dimensions, requiring decisions about the spatial, organizational (i.e., from individual to global), and temporal scales of analysis.

Spatial

Defining the geographic area of interest is often cited as the first step in a VA (WHO 2013; Schröter et al. 2005). While VAs can assess threats at the global level, they can also scale to specific regions, like arable lands, forests, or coasts (Allison et al. 2009). The selection of suitable vulnerability indicators depends on geographical space, particularly distinct landscapes or biomes (e.g., indicators for a saltwater system will be different than indicators for a freshwater system). Direct physical impacts of climate change can vary drastically over even small spatial gradients (e.g., differential impacts of sea level rise on coastal flats versus nearby uplands). The distribution of physical impacts does not always align with political boundaries, adding additional layers of complexity to understanding exposure, sensitivity, and adaptive capacity in relation to climate change impacts (Barsley et al. 2013).

Organizational

As with spatial scale, vulnerability is spread unevenly across different scales of human organization. While a nation may be largely resilient, smaller communities within that nation may be vulnerable to specific changes. For example, Sweden as a whole is well-connected to international markets, and so has high adaptive capacity in the face of economic disruption linked to climate change. However, communities of reindeer-herders within Sweden operate in small economic networks with fewer ties to other markets, and so have less adaptive capacity and more acute vulnerability (Fig. 5) (Keskitalo and Kulyasova 2009). Conversely, a nation may be generally vulnerable, while certain citizens remain safe. This often occurs when wealth is unevenly distributed. For example, in Vietnam, wealthy coastal districts have the resources and political power to maintain coastal dikes independently from the national government, which reduces local-scale vulnerability (Adger and Kelly 1999).

Oftentimes, VAs focus on an individual or household scale (Barnett and Eakin 2015). Household behavior can be aggregated through methods

Vulnerability Assessments for Evaluating the Sensitivity of Infrastructure to Environmental Change, Fig. 5 The Sami people face vulnerability to climate change, in spite of living in a developed country with generally high adaptive capacity. (Norman Tsui, Unsplash). (Norman Tsui 2017. Photo from: Unsplash, https://unsplash.com/license) like agent-based modeling, to quantify community-wide or regional vulnerability. National assessments, such as those required for UN member states, face the challenge of incorporating the variation inherent within their state and attempting to compare those differences across multiple states (WHO 2013).

Interactions between scales can influence vulnerability, too. For example, national policies may influence municipal policy, thus influencing a household's exposure or adaptive capacity. Increasing globalization further extends the influence of large organizational scales on local processes (Keskitalo and Kulyasova 2009). Indeed, globalization and climate change together create large-scale change that will produce varying patterns of local-scale sensitivity and adaptive capacity (O'Brien and Leichenko 2000). Nested-scale VAs that examine influence and interaction at multiple organizational scales can identify such cross-scale drivers of vulnerability, while providing findings at a level applicable to decision-makers.

Temporal

A central challenge in choosing a timescale for analysis lies in navigating the needs of decision-makers that tend to deal with near-term concerns, while climate-linked vulnerability may seem like a longer-term issue (WHO 2013). Additionally, different adaptation decisions have different lifespans. For example, the construction of a climate-proof building will last for several decades (Watson and Adams 2010), but an agricultural intervention, like increasing irrigation, may only last for the duration of the growing season (Sutton et al. 2013). VAs must consider the longevity of past, current, and future risks and adaptation. When modeling future climate change patterns, models must be extended across long timeframes to take these lasting impacts in account. It is thus imperative that researchers recognize and are forthcoming about the limitations of their ability to predict complex systems with confidence (Patt et al. 2005).

Scaling Up

As described above, vulnerability is not spread evenly across space, organization, or time (O'Brien and Leichenko 2000). To maximize accuracy and utility, VAs must be accordingly context-specific (Turner et al. 2003). However, VAs occasionally uncover broad underlying patterns of vulnerability that can help guide assessment questions in other locations or scales of organization. For example, a VA of impoverished fishing communities in Mali revealed that the most effective adaptation would not be interventions targeting the fishing sector itself, but increased access to micro-loans and credit across the broader community (Mills et al. 2011). The overall finding – that non-sector change might be the most effective intervention – can now be examined and tested in VAs across other systems.

Limitations

VAs are subject to a wide variety of logistical and methodological limitations. Logistically, the assessment may be limited by lack of funding, organizational capacity or high-quality data. Methodological approaches still struggle to quantify and parse the full complexity of the social-ecological systems in question; unpredictable interactions, feedback loops, and chaos limit the predictive power of even highly sophisticated models. These challenges are further compounded by disciplinary boundaries that still impede the communication of environmental, economic, and social information (FAO 2013).

A different suite of barriers are present after the VA is completed. Communication is an essential part of the VA process, but ensuring that the assessment reaches the appropriate decision-makers in a format that is accessible and relevant can be challenging. Additionally, effectively communicating uncertainty is a hurdle in translating VAs into actionable policy, as communicators must balance representation of both uncertainty and confidence in the findings (Patt et al. 2005).

Finally, effective communication does not ensure that assessment-driven adaptation will occur. The complex risks uncovered in VAs often result in complex adaptive strategies.

Decisions to implement these strategies can be impeded by lack of financial or human resources, political disinterest, legal constraints or information and communication barriers (WHO 2013). However, the risk of not acting on VA recommendations can be mitigated by involving decision-makers throughout the VA in a participatory way and identifying feasible adaptive management plans in association with the VA process (Cadag and Gaillard 2012; UNFCCC 2011).

Best Practices

The UN Framework Convention on Climate Change (UNFCCC) has compiled a set of good practices for completing a VA. Broadly, VAs should acknowledge and utilize varied sources of knowledge, be place-specific, and account for the complexity of the system by recognizing multiple drivers of change. In addition, they should be human-focused, providing insight into the most vulnerable groups and adaptations that will lessen the harm these groups experience (Table 1, Brugère and De Young 2015).

In addition to these practices, an important series of questions should be considered when conducting or interpreting VAs:

- Who is the driver behind the VA?
- Who is funding the VA?
- What biases may be present in the indicators and methodologies used?
- Who is accessing this VA to determine adaptation plans?

Considering such questions helps identify bias and ensures that VAs are reaching an audience that will benefit from them.

Vulnerability Assessments for Evaluating the Sensitivity of Infrastructure to Environmental Change, Table 1 Table adapted from UNFCCC 2011. Good practices for VAs determined at a meeting of practitioners at the Nairobi Work Program (NWP) on impacts, vulnerability, and adaptation to climate change

Area	Good practice
Scope	Engage all relevant stakeholders, consider natural and social contexts, and determine focus and outcomes
Selection of methods and tools	Select best tools to the purpose, while considering resource constraints
Quantitative and qualitative	Consider both types of analyses as helpful
Present and future	Complete detailed analyses on current trends for climate, socioeconomic patterns, and adaptation responses, particularly when analysis on future vulnerability is impacted by uncertainties
Stakeholders	Include key stakeholders at every stage of the process
Collaboration	Include inputs from a wide range of disciplines; develop effective collaboration to improve credibility of assessment results
Transparency	Be transparent about underlying assumptions and caveats of the assessment process and results

Case Studies

The following two case studies demonstrate how VAs can be used to evaluate a developing nation's critical infrastructure (for an overview, see Table 2). The first uses a quantitative model to assess the vulnerability of Uzbekistan's agriculture sector to warming and drought. This case demonstrates how a VA can be used to assess biophysical impacts first, then expanded to incorporate multiple factors at a broader organizational scale. The second VA is from the small Caribbean island of Anguilla and was carried out with participation of the local fishing community to determine fishing sector vulnerability to climate change. Though just a small sample of available VAs, these demonstrate some of the variety in VA methodology, scale, and implementation, as well as demonstrating their links to infrastructure and industry.

Case Study #1: The Vulnerability of Uzbekistan's Agriculture Sector to Climate Change

Uzbekistan is a Central Asian country situated between Afghanistan, Kazakhstan, Kyrgyzstan, Tajikistan, and Turkmenistan (Fig. 6). Although

Vulnerability Assessments for Evaluating the Sensitivity of Infrastructure to Environmental Change, Table 2 Overview of VA case studies

Location	Uzbekistan	Anguilla
Sector	Agriculture	Fisheries
Vulnerability approach	Initially: Outcome vulnerability In follow-up report: Context vulnerability	Context vulnerability
Methodology	Initially: Quantitative (modeling crop yield) In follow-up report: Qualitative (consultation and ranking) Participatory (stakeholder consultation)	Quantitative (spatial relationships) Qualitative (consultation and ranking) Participatory (P3DM)
Spatial scale	3 Agro-ecological zones (AEZs); 5 river basins; $\approx$450,000 km^2	8 Fishing villages; entire island; $\approx$90 km^2
Organizational scale	National	Territory-wide
Temporal scale	Decadal	Decadal
Exposure	Higher temperatures and longer growing season Lower and more variable precipitation More frequent hail, drought, flood, and heat-wave events Increased crop pests and disease	Sea level rise More variable precipitation More extreme weather events, including droughts, floods, and storms Coral reef ecosystem decline from warming and acidifying seas and introduced species
Sensitivity	High reliance on irrigation for field crop production Field crop production composed of relatively few crop types Temperature and precipitation change reduces yield for most crops Aging irrigation infrastructure limits water availability Water limitation is most extreme during growing season Rural areas have high poverty rates and are reliant on agricultural livelihoods	High reliance on marine-resource industries, including fishing and marine tourism, for economy High reliance on precipitation for clean drinking water Lack of human resources and funding to implement climate change and disaster adaptation practices Lack of existing key legislation to ensure investment in fisheries sector Low levels of trust and cooperation among fishers
Adaptive capacity	Certain crops (grasslands, alfalfa) have higher productivity under predicted climate scenario AEZs with marginal rain-fed production will have less adaptive capacity than irrigated areas Ongoing organizational change in farm management is increasing flexibility in crop choice Extension agency provides training and information to farmers	Government support for establishing committee to assess risks and adaptation for fisheries sector Growing tourism sector provides livelihood alternatives to fishing Diversity of species still available for fishing
Suggestions to reduce vulnerability	Improve irrigation infrastructure Identify and increase use of crops that are climate resilient Develop extension agency to increase training in water-efficient farming practices	Strengthen government agencies to enable coastal zone management Build adaptive capacity of fishers through knowledge and resource sharing Identify financing opportunities to promote alternative livelihoods Climate-proof coastal infrastructure

Vulnerability Assessments for Evaluating the Sensitivity of Infrastructure to Environmental Change, Fig. 6 Map of Uzbekistan (U.S. Central Intelligence Agency). (CIA 1995. Photo from: Wikimedia Commons)

the vast majority of Uzbekistan consists of sandy deserts, its agricultural sector comprises 17% of its GDP and employs 26% of its labor force (United States Embassies 2017). It is the world's fifth largest cotton producer and second greatest cotton exporter (UNDP 2016). Over half of all farms in Uzbekistan are *dehkan* farms, run by individual households (Lerman 2008), and 80% of food consumed in Uzbekistan is produced via domestic agriculture (Fig. 7).

Climate change could potentially diminish Uzbekistan's agrarian sector. Most Uzbek farms rely on irrigation, which uses 90% of the country's surface water. Warming air temperatures enable

Vulnerability Assessments for Evaluating the Sensitivity of Infrastructure to Environmental Change, Fig. 7 A field hand packs raw cotton into an apron in an Uzbek cotton field (Wikimedia Commons). (Shuhrataxmedov 2012. Photo from: Wikimedia Commons, https://creativecommons.org/licenses/by-sa/3.0/deed.en)

greater evaporation of the waters that farmers use. Irrigation infrastructure, while extensive, operates at a less-than-optimal efficiency. Additionally, as water evaporates and land is degraded by irrigation mechanisms, saltwater from the Aral Sea intrudes arable tracts of land. Ultimately, land use change and climate change threaten water resources, agriculture, and food security throughout Uzbekistan (UNDP 2016). Given that farming is a salient Uzbek industry, understanding how climate change threatens agriculture infrastructure is critical.

The World Bank, in partnership with Uzbekistan's national government, contracted private companies (Industrial Economics and FutureWater) to assess the impact of climate change on specific crops cultivated in Uzbekistan. Through an iterative VA process, analysts considered impacts of climate change from individual crops, to farms, to the nation's agricultural industry as a whole. Ultimately, the products of this report were used to prioritize options for national policy and capacity building to allow industry adaptation.

In the first VA, analysts considered impacts on crop yields and water availability under increasingly severe climate change scenarios (baseline, low, median, and high). Analysis spanned the nation's five river basins and agro-ecological zones (AEZs), over a multi-decade timeframe. Analysis of crop yields found that, at low and median climate scenarios, yields are projected to experience minimal negative impacts. Certain crops, including alfalfa and grasslands, are expected to experience increasing yield due to warmer temperatures that occur at the beginning and end of the growing season. Grasslands also benefit from the increased precipitation that low and median climate scenarios will bring. Under a high climate change scenario, reduced rainfall restricts yield across all crops. While water requirements changed only minimally in the low and median climate scenarios, the water needs of nearly all crops increase in the high climate scenario. Alfalfa and spring wheat are the exception; these crops experience a decrease in their water need under high climate change.

This outcome VA provided the recommendation of specific adaptation measures at the individual level. These included increasing the amount of fertilizer applied to crops, growing crop varieties with better water use efficiency, increasing the amount of water used during irrigation, and overwatering crops to drive salts deeper underground and reduce soil salinity. At a broader level, this VA was used to raise awareness about the impacts of climate change on the agrarian sector and begin to develop potential adaptation options and capacity at different scales for managing crop production and water use.

In a second, more in-depth VA, modeling analysis was combined with qualitative and participatory analyses of threats and adaptive capacity. Collectively, domestic and international agriculture experts and Uzbek farmers developed 56 adaptation options concerning farm management, government-driven programs, and infrastructure. The report delineated how policies and institutions could facilitate adaptation measures at the national scale and within different AEZs. Additionally, a timeline for executing adaptations was included based on the amount of lead time that would be required to implement them.

Infrastructure was a highlighted avenue for adaptation, with 25% of adaptation options focused on how infrastructure adaptation could secure Uzbek agriculture against climate change. The recommended changes to infrastructure largely concerned water use: without efficient irrigation systems and reliable water reservoirs, farmers may not have sufficient water resources for crops during critical periods in the growing season. Conversely, inadequate drainage capabilities could cause farmlands to flood during intense storms. Infrastructural changes to address water management, including improving preexisting drainage and irrigation systems and installing infrastructure for collecting meteorological data crucial for crop and drainage management, are key infrastructure changes that could significantly reduce the vulnerability of farmers and the broader Uzbekistan agricultural system.

Overall, the integration of quantitative modeling and qualitative farmer- and expert-opinion elicitation allowed this VA to robustly identify climate change sensitivities and adaptive capacity, and better direct industry adaptation across scales to meet those factors.

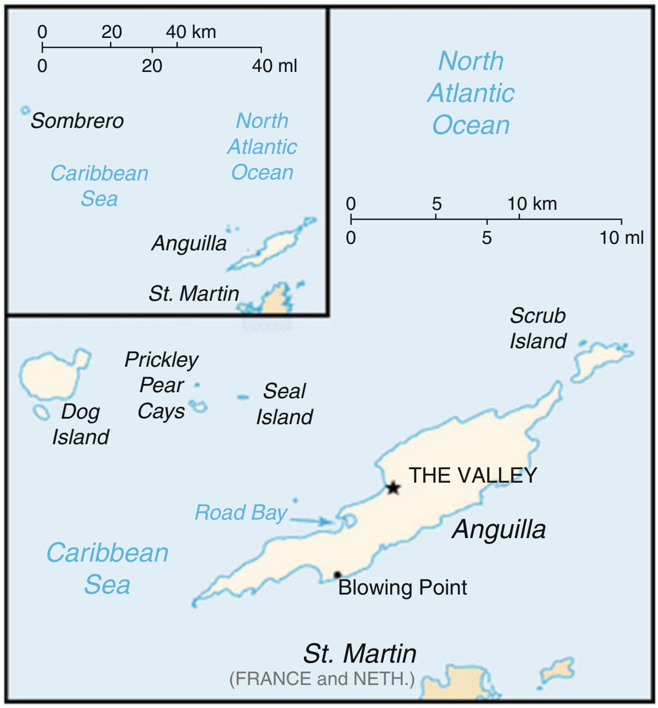
Case Study #2: The Vulnerability of the Anguilla Fisheries Sector

Small-island developing states (SIDS) are particularly vulnerable to climate change impacts. As islands, these areas face high exposure to biophysical climate change impacts, including sea level rise and intensifying storms. As developing states, they have fewer financial resources available for adaptation measures. Furthermore, many SIDS are marked by resource-dependent industries, creating tightly linked systems in which impacts of climate change reverberate across social and ecological factors and can exacerbate vulnerability. SIDS fisheries sectors have been highlighted as being especially vulnerable to climate change due to this feedback (Monnereau et al. 2015).

This study focused on Anguilla, the British Overseas Territory in the Eastern Caribbean Sea (Fig. 8). Anguilla's island economy relies heavily on marine resources for tourism and fishing. The latter is a significant economic contributor and major source of food and local livelihoods. In 2011, Anguilla drafted a Climate Change Policy describing goals to understand and address climate change impacts on livelihoods, health, and well-being, with specific reference to marine resources. In 2017, the Caribbean Natural Resources Institute (CANARI) worked with Anguilla's Department of Fisheries and Marine Resources and University of the West Indies to extend the climate change adaptation work through a VA focused on Anguilla's fisheries. The VA considered the impact of climate change on six social-ecological categories: (1) coastal and marine biodiversity and ecosystems; (2) cultural heritage, values, and social networks; (3) livelihoods and socioeconomic practices; (4) settlements and infrastructure; (5) safety at sea and emergency response, and (6) water resources.

Focusing on the fisheries sector, the VA emphasized vulnerability in coastal communities, fishing grounds, landing sites, and important coastal and marine ecosystems. However, through the VA methodology, participants were also able to contribute knowledge about the entire island of Anguilla, thus expanding the spatial scale. Impacts and adaptations were considered over a multi-decade timeframe and spanned the organizational scale from individual Anguillians to territory-level policy.

The VA was highly participatory (Fig. 9). It employed a "participatory 3-D mapping" (P3DM) process that brought stakeholders together to populate a 3D model of Anguilla with locally specific knowledge of tangible (e.g.,



Vulnerability Assessments for Evaluating the Sensitivity of Infrastructure to Environmental Change, Fig. 8 Map of Anguilla (CIA 2004). (CIA 2004. Photo from: Wikimedia Commons)

Vulnerability Assessments for Evaluating the Sensitivity of Infrastructure to Environmental Change, Fig. 9 Participants create contour map of Anguilla (CANARI 2018). (Photo credit: Ainka Granderson, Caribbean Natural Resources Institute). (Ainka Granderson 2018. Photo from: CANARI 2018)

flood areas, important fishing grounds) and intangible (e.g., sacred areas, culturally significant boundaries) features. While a participatory approach is time- and labor-intensive, it provides a wealth of information that may not be captured in a conventional VA, as it is accessible to often-overlooked groups including young, elderly, and illiterate stakeholders. Furthermore, it allows for ownership of the process and results to stay with the community (Mills et al. 2011).

The participatory process was carried out in three major phases. In phase 1, organizers defined the purpose of the assessment, identified and analyzed stakeholders, and began mobilizing stakeholder involvement. In phase 2, stakeholders met at a 2-day workshop to create a 3D map of Anguilla populated with information concerning fishery vulnerability and adaptation that was used to guide fishery analysis and community decisions. The map was then returned to the community during a ceremonial hand-off. In the third and final phase, researchers used photographs of the map to create long-term GIS datasets and worked with the community to consider future plans for use of the data.

Climate change hazards, such as sea level rise and worsening storms, impact all of these categories and have particular effects on infrastructure and industry. Specific climate change impacts related to infrastructure in Anguilla include loss of and damage to coastal settlements, hotels, telecommunication systems, and power stations. Changes to reef ecosystems and marine storm patterns combine with infrastructure loss that impact coastal Anguillian industries: tourism is likely to decline with the combination of reduced ecosystem health and land-based infrastructure while fishing is likely to become harder and more dangerous due to a decline in fished species and the loss of safe wharfs and fueling stations. Social change adds an additional layer to these vulnerabilities as tourism operators and fisher folk without access to alternative livelihoods will be particularly at risk to the change in infrastructure and industry due constraints on adaptive capacity.

The VA suggested adaptation measures that focus at the territory-wide level of organization within Anguillian fisheries. Infrastructure changes, namely, climate- and storm-proofing coastal structures and telecommunication structures, were key opportunities for adaptation. Industry-level adaptation suggestions included support for fishers. The Department of Fisheries and Marine Resources was highlighted as a government agency that could help guide fisher adaptation through improving fishing practice (e.g., providing technologies and training to increase safety and sustain catch for Anguillian fishers) and policy (e.g., strengthening the marine elements of existing territory-scale legislation on climate change adaptation).

This VA revealed some positive impacts of climate change adaptation, including increased interest in alternative livelihoods, like the development of aquaculture and green construction industry, and appreciation for traditional knowledge in determining adaptive response. Stakeholders were actively engaged participants throughout this process, and the physical 3D map was formally presented to key community leaders following the workshop. Participants and key stakeholders used the VA to identify priorities for climate change adaptation actions.

Ultimately, this VA proved the participatory 3-D mapping approach to be a valuable tool, useful for gathering diverse local knowledge, identifying key spatial relationships, and engaging stakeholders in adaptation planning. If patterns from previous P3DM approaches hold, the networks and conversations generated between engaged community-members during this process will enhance support for and consensus of adaptation measures for Anguilla (Cadag and Gaillard 2012).

Conclusion

The UNSDGs strive to improve social and planetary welfare in this era of rapid global change. SDG 9, Industries, Innovation and Infrastructure, focuses on developing the physical and societal scaffolding that supports economic growth, health and education opportunities, and the development of environmentally responsible industries and technologies (Ostrom 1993; UN General Assembly 2015). However, successfully achieving these objectives requires grappling with their sensitivity to ecological, social, and political change.

As SDG 9 recognizes, industry and infrastructure have an important role to play in worldwide sustainable development in the coming century. Infrastructure and industry have the potential to exacerbate exposure and sensitivity or to enhance adaptive capacity. The case studies presented here offer a brief glimpse of that complexity. In Uzbekistan, suboptimal irrigation infrastructure contributes to water scarcity – but improving this infrastructure has the potential to increase food security. In Anguilla, increasing beach erosion and storm surge threatens the tourism industry, leaving Anguillians with narrowed livelihood alternatives – but the risks of climate change promote increased interest in new industries including aquaculture and green construction. VAs allow the analysis necessary to understand how industry and infrastructure fit into the complex web of environmental, social, and economic conditions facing developing communities and provide insight into priorities for adaptation.

VA practitioners have a responsibility to carefully consider the purpose, methodology, and communication of their assessment. They should also think broadly: sources of vulnerability may lie outside of the bounds of their home disciplines and best solutions may fall in nontarget sectors. Done well, VAs can adeptly examine complex social-ecological systems to reveal important sensitivities and adaptive capacities of the individuals, households, and communities most at risk of climate change impacts.

Cross-References

► Adaptive Capacity
► Climate Change Adaptation: Infrastructure and Extreme Weather
► Risk-Based Approach to Sustainable Infrastructure

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