



Tool

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A Practical Guide to Vulnerability Assessments for Stormwater Agencies

Approaches, Applications, and Best Practices

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About This Tool

The guide serves both as a reference and a toolkit to help stormwater agencies prioritize investments, foster resilience, and improve compliance and adaptation planning for stormwater infrastructure in the face of complex, multi-hazard conditions. It offers a systematic, step-by-step approach for developing and conducting vulnerability assessments that considers each agency's unique resources, goals, and constraints. The guidebook reviews assessment methodologies ranging from expert judgment, scorecards, indicator-based assessments, spatial analysis, and detailed modeling. It provides guidance on matching assessment approaches to agency capacity—from low-resource settings using qualitative methods for regulatory compliance, to high-capacity agencies leveraging advanced data and more rigorous qualitative methods with stakeholder engagement for strategic planning. The guidebook also includes lessons from literature and case studies, highlighting practical applications, common challenges, and best practices.

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A Practical Guide to Vulnerability Assessment for Stormwater Agencies: Approaches, Applications and Best Practices

Purpose and Scope

This guidance is designed to support stormwater agencies in developing and implementing effective vulnerability assessments tailored to their unique needs, goals, and resource constraints. As climate change, extreme weather, and evolving regulatory environments create new and complex challenges for stormwater management, systematic vulnerability assessments have become essential tools for identifying which systems, assets, and populations are at greatest risk, prioritizing investment decisions, and supporting long-term resilience and compliance efforts.

This document provides practical, step-by-step guidance for agencies to select an appropriate vulnerability assessment approach. It reviews a range of methodologies—from foundational approaches like expert judgement and scorecards, to advanced techniques such as spatial analysis and modeling—and offers advice on matching assessment methods to agency capacity, available resources, and timelines. Real-world case studies and lessons learned from scientific literature are included to illustrate applications, challenges, and best practices.

Key Goals

This document is intended to guide agencies in designing and conducting vulnerability assessments that are:

- *Right-sized to intended use:* Assessments should be appropriately scoped—not overly complex or too generic—but matched to the specific needs and intended uses of the assessment.
- *Meaningfully connected to planning and decisionmaking:* Vulnerability assessments should be designed and viewed as key contributors to planning and decision processes, with outputs that are specific and actionable and that directly inform investment, operational, and adaptation strategies.

In developing this document, a common theme in our review of vulnerability assessments was the frequent disconnect between the assessment process and its use in decision making. In many cases, agencies conduct the assessment as a stand-alone exercise, only later referencing its findings during planning, design, or operational decisionmaking. For example, some agencies invest significant effort in complex modeling but ultimately reduce the results to simple risk categories for planning purposes. In these cases, a more streamlined approach could have been enough and used fewer resources. Conversely, planning and decision processes often proceed independently of vulnerability assessment findings, with strategies or designs developed first and only later checked against assessment results. While this retrospective use can be valuable, it

raises questions about whether existing plans adequately address identified vulnerabilities or simply acknowledge them after the fact.

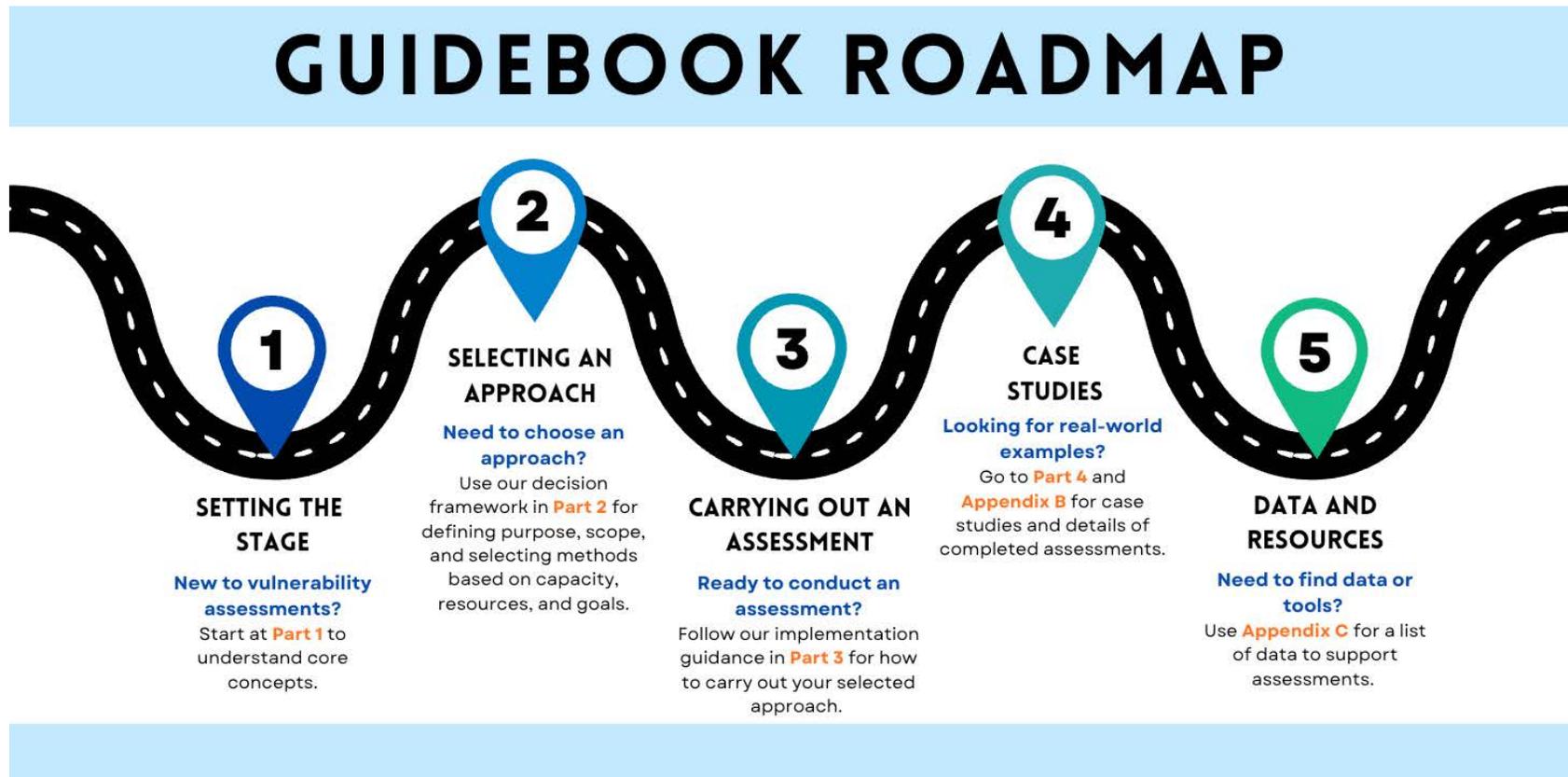
This guidance is intended to help agencies avoid these pitfalls by ensuring that appropriate vulnerability assessment approaches are selected and implemented with a clear and deliberate connection to their intended use. By aligning assessment methods with decisionmaking needs from the outset, agencies can ensure that findings meaningfully inform the development, prioritization, and design of solutions.

In this report, “stormwater agency” refers broadly to any public entity responsible for some aspect of stormwater management, whether as a dedicated department or within a wastewater utility, flood control district, public works division, or other organizational structure.

Roadmap for this Document

This guide is designed to serve both as a reference and a practical toolkit for stormwater agencies at all levels of capacity. Users are encouraged to navigate the document according to their specific needs, whether seeking foundational concepts, step-by-step guidance, or in-depth case studies and resources. Figure 1 provides an overview of this roadmap.

Figure 1. Roadmap for this Document



As shown in Figure 1, the document is organized into the following main sections and appendices:

1. *Part 1: Setting the Stage* introduces foundational concepts, definitions, and key terms related to vulnerability assessments in the context of stormwater management. This section provides the conceptual framework for understanding vulnerability, including the roles of exposure, sensitivity, and adaptive capacity, and explains why vulnerability assessments are essential for effective planning and resilience.
2. *Part 2: Selecting an Approach* presents a stepwise, decision-support framework to help agencies clarify the purpose and scope of their vulnerability assessments. This section guides users through evaluating their resources, technical capacity, and timelines, and provides tools to help select the most appropriate assessment approach or combination of approaches. It also discusses how to match methods to agency goals, regulatory requirements, and available data.
3. *Part 3: Carrying Out a Vulnerability Assessment* details the major methodological approaches to vulnerability assessment, including expert judgement, scorecards, indicator-based assessments, spatial analysis, statistical analysis, and modeling. For each approach, the section provides practical implementation guidance, discusses strengths and limitations, and offers real-world examples to illustrate application. This part also includes a step-by-step framework for conducting an assessment, from goal-setting to communicating findings.
4. *Part 4: Vulnerability Assessment Case Studies* showcases a series of case studies from diverse agencies and regions, illustrating how different approaches have been applied in practice. These examples highlight lessons learned, challenges encountered, and best practices for tailoring assessments to local contexts and resource constraints.
5. *Appendix A. Background and Methods* summarizes the literature review and stakeholder interviews that informed the development of this guide. This appendix provides additional context on the evolution of vulnerability assessment methods, common challenges, and the rationale behind the guidance presented in the main text.
6. *Appendix B. Referenced Vulnerability Assessments* provides detailed summaries of the vulnerability assessments referenced throughout the guide, including key features, approaches used, and lessons learned. This appendix serves as a resource for agencies seeking examples or models for their own assessments.
7. *Appendix C. Data Resources for Carrying out a Vulnerability Assessment* lists and describes data sources, tools, and platforms that can support each stage of a vulnerability assessment. This includes sources for infrastructure, social, environmental, and climate data, as well as modeling and mapping tools.

While this guidance compiles best available knowledge and synthesizes lessons from a range of agency experiences, it is important to recognize its limitations. The document is not a substitute for detailed engineering analyses where required, nor does it capture every possible tool or scenario. Local data availability, institutional capacity, and regional regulatory context may shape how specific recommendations can be applied. Agencies should view this guidance as a flexible and adaptable foundation—one to be supplemented with expert consultation, local engagement, and ongoing learning to best meet their community's needs.

Finally, this guidance document was developed through synthesizing content from a range of interviews, literature and completed vulnerability assessments. We have organized the document to present the synthesis and our recommendations first. Appendices A, B and C contain the background, our findings and the references we used.

Part 1: Setting the Stage

What is a Vulnerability Assessment?

For the purposes of this guidance, a vulnerability assessment is defined as the assessment of a system's susceptibility to hazards. For stormwater agencies, this means evaluating how various elements of their systems—such as assets (e.g., general building stock or natural resources), functions (e.g., reliability of stormwater outfalls, transportation, or electricity), or populations (particularly sensitive subgroups)—are at risk when exposed to specific hazards. The goal is to identify not only what and who is at risk, but also why certain assets or groups are more susceptible, and what can be done to reduce that risk.

For stormwater agencies, this means looking closely at a range of system elements. These include physical assets like stormwater pipes, culverts, pump stations, and treatment facilities, as well as the broader built environment—roads, buildings, and other infrastructure that could be affected by hazardous events. But vulnerability assessments go beyond just infrastructure. They also consider the functions these systems provide (such as reliable drainage, water quality considerations, or flood protection), the populations served (with special attention to groups who may be more affected by disruptions), and the environmental features—like wetlands or green spaces—that help manage stormwater and support community resilience.

A widely used framework, as described by the Intergovernmental Panel on Climate Change (IPCC), understands vulnerability as “the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes” (IPCC, 2001).¹ Vulnerability is viewed as a function of the character, magnitude, and rate of hazard to which a system is exposed, its sensitivity, and its adaptive capacity. Simplified, this means vulnerability depends on three key factors:

- **Exposure:** This refers to whether, how, and how often system elements are exposed to hazards. For example, is a pump station located in a flood-prone area? Are certain neighborhoods more likely to experience heavy rainfall or storm surges?
- **Sensitivity:** This is about how much those assets, functions, or populations would be affected if a hazard occurs. Sensitivity can be influenced by factors such as the age or condition of infrastructure, the design standards in place, or the socioeconomic status of a

¹ While the original IPCC framework is still widely used, more recent IPCC reports (AR5 and AR6) redefine risk as a function of vulnerability, exposure, and hazard, with sensitivity and adaptive capacity now considered under the umbrella of vulnerability.

community. For example, older pipes may be more likely to fail during a storm, or under-designed pump stations may not be able to handle increased runoff volumes.

- **Adaptive Capacity:** This describes the ability of the system or community to reduce potential impacts or recover from them. Adaptive capacity might include having backup systems, access to emergency resources, or strong community networks that help people respond to and recover from hazards.

It is important to note that while specific definitions may vary—with differing emphasis on social, economic, environmental, or physical system elements—all follow the broad logic of characterizing hazards (capturing the concept of exposure), estimating the impacts on system elements (capturing sensitivity), and, less frequently, considering the degree to which systems can adapt (adaptive capacity). Box 1 provides an example of a vulnerability assessment using these elements.

Stormwater agencies conduct vulnerability assessments for a variety of reasons, including capital improvement planning, regulatory compliance, project design and land use planning. Assessments are typically carried out in relation to a range of hazards. The most common are those related to climate and weather, such as extreme rainfall, riverine or flash flooding, coastal surge, drought, and urban heat waves. Increasingly, agencies are also considering how risks may change over time, including changes in precipitation patterns, more frequent or intense storms, sea level rise, and the possibility of multiple hazards occurring at once (for example, a heatwave during a major storm). Non-climate hazards, such as infrastructure failure or water quality problems, may also be included, especially when they can interact with climate-related risks.

In practice, a vulnerability assessment helps agencies prioritize where to invest limited resources, which assets or communities need the most protection, and what kinds of adaptation or resilience strategies will be most effective. By understanding not just what is vulnerable, but why, agencies can make more informed decisions that improve both day-to-day operations and long-term planning.

Box 1. Vulnerability Assessment for Southeast Palm Beach County, Florida

The Coastal Resilience Partnership of Southeast Palm Beach County, Florida conducted a comprehensive climate change vulnerability assessment involving eight jurisdictions in the region (Coastal Resilience Partnership, 2021). Their approach assessed vulnerabilities to a broad spectrum of climate-related hazards, including flooding, and was designed to inform adaptation strategies for both the region as a whole and for individual member communities.

- **Exposure** was evaluated by mapping the intersection of community assets and functions—such as critical facilities, water infrastructure (including green infrastructure), economic factors, natural resources, people and socioeconomics, property, and roads & mobility. For flooding, areas projected to be inundated were assessed under a series of flood scenarios.
- **Sensitivity** was assigned based on both the exposure status of an asset and the potential impact if it were affected. For example, assets such as major medical facilities or large apartment buildings were designated as having high sensitivity if exposed to flooding due to the significant consequences for public health and welfare. The assessment designated sensitivity as high if a high-impact asset was exposed, medium if a lower-impact asset was exposed, and low if the asset was not exposed. The combination of exposure and sensitivity was conceptualized as “potential impact”.
- **Adaptive capacity** was evaluated for physical assets based on the construction date relative to floodplain management standards. Assets built after 2017 qualified as having high adaptive capacity due to stricter elevation requirements (first-floor elevation at least one foot above base flood elevation). Assets constructed between 1982 and 2017 were classified as having medium adaptive capacity (first-floor elevation at base flood elevation), and those built before 1982 were considered to have low adaptive capacity due to less stringent standards. In some cases, assets not exposed to hazards also qualified as having high adaptive capacity.

The results of these analyses were presented spatially, allowing planners to visualize vulnerability across geographies and assets, and to identify intersections of physical and social vulnerability (e.g., areas where high-risk floods overlapped with high concentrations of vulnerable populations or critical services). The findings informed the prioritization of adaptation strategies, which included infrastructure projects, land use and regulatory updates, policy and management recommendations, capacity building, public outreach, and identification of funding needs, with the overall framework designed for reusability and to guide future resilience efforts in the region.

How Do Agencies Assess Vulnerability?

There are a variety of approaches available for conducting vulnerability assessments, each with different levels of complexity, data and resource requirements, and target applications. Table 1 contains several commonly used approaches, including qualitative methods like expert judgements and vulnerability scorecards to quantitative techniques such as GIS-based spatial analysis and hydraulic modeling. Qualitative approaches can be relatively quick and resource-light, making them useful for initial screenings, but they can also be applied in highly systematic and rigorous ways. Quantitative approaches often involve numerical data and computational tools, which can support detailed analysis, but they too can vary in resource intensity and rigor.

All of the approaches in Table 1 can consider historical and future vulnerabilities. Assessments can incorporate historical data (e.g., past flood events, precipitation records, or observed damages) and projected information (e.g., future precipitation intensities, sea level rise estimates, or demographic shifts). Historical data help characterize existing vulnerabilities and trends, while projected data allow agencies to consider how those vulnerabilities may change under future conditions. Table C.1 in Appendix C provides further detail on the use of historical and projected data for each approach.

Table 1. Common Vulnerability Assessment Approaches

Approach	Description	Data	Example
Expert Judgement	Structured discussions with subject matter experts to identify and assess vulnerabilities. Can range from informal consultations to formal, well-documented processes. Subject matter experts include local community member and decisionmakers.	Expert panels, stakeholder input	Convening city engineers and local officials to discuss which neighborhoods are most vulnerable to flooding.
Scorecards	Scoring assets/functions based on exposure, sensitivity, adaptive capacity. Can use simple scales or more complex scoring frameworks.	Local knowledge, simple scoring tools	Using a scorecard to rate each asset (e.g., stormwater pump station) on a scale of 1–5 for vulnerability to flooding.
Indicators	Using indicators (e.g., % impervious area, age of infrastructure) to rate vulnerability. Indicator sets can be simple or multi-dimensional.	Data on selected indicators	Calculating vulnerability scores for neighborhoods based on % impervious surface and average pipe age. SVFs are another example.
Spatial Analysis	Overlaying spatial data on hazards and assets to quantify exposure. This can range from basic visual mapping to advanced geospatial analysis.	High-quality GIS and hazard data	Mapping flood zones and overlaying locations of critical infrastructure to identify at-risk assets.
Statistical Analysis	Using historical data to estimate probability and consequences of hazards. Techniques may range from basic trend analysis to sophisticated statistical modeling.	Historical event and damage data	Analyzing 30 years of precipitation records to estimate the annual probability of stormwater system failure.
Modeling	Simulating stormwater system response to various hazard scenarios. Models can be relatively simple or highly detailed depending on purpose and resources.	Detailed system and climate data	Running hydrologic and hydraulic models to predict how the stormwater network will perform during a 100-year rainfall event.

SOURCES: E.g., Cooke and Goossens, 2010; Berke et al., 2021; Borzi, 2023; Ebert et al., 2009; Kim and Kim, 2013; Nasrollahi et al., 2025

Agencies often blend several approaches throughout the vulnerability assessment process to maximize the strengths of each and offset their respective limitations. For example, qualitative methods such as expert workshops and vulnerability matrices are frequently used at the outset to identify priority hazards, incorporate local knowledge, and build consensus among stakeholders. These approaches are particularly valuable when data are scarce or when engaging a broad set of community perspectives is critical. As agencies refine their focus, they may integrate quantitative tools—such as spatial analysis, indicator-based scoring, and system modeling—to deliver more detailed estimates of exposure, sensitivity, and sometimes adaptive capacity across assets and populations. This layered strategy allows agencies to tailor their assessment activities to the available technical capacity, data availability, institutional context, and specific decision contexts, such as long-term infrastructure investments or regulatory compliance. Combining both qualitative and quantitative approaches can also help agencies overcome subjectivity, as in the

case of qualitative approaches, or data biases, gaps and limitations that can occur with quantitative approaches.

Vulnerability vs. Risk: What's the Difference—and Does It Matter?

In concept, vulnerability assessments and risk assessments are distinguished by their focus and underlying frameworks. A vulnerability assessment centers on understanding a system's susceptibility to harm from hazards, emphasizing exposure, sensitivity, and adaptive capacity as primary components. It seeks to describe how and why specific assets, functions, or populations are vulnerable to particular hazards, often layering social, infrastructural, and environmental dimensions. In contrast, a risk assessment is typically defined as the evaluation of the likelihood and consequence of a hazardous event, bringing together probability (or frequency) and impact to estimate expected losses or outcomes.

However, in practical application—especially within the context of stormwater and climate adaptation planning—these distinctions are often blurred. Both vulnerability and risk assessments involve characterizing hazards, mapping exposure, evaluating potential impacts on system elements, and considering the ability to cope or recover. The analytical steps, data, and tools used frequently overlap, and both assessments serve the common purpose of identifying which areas, assets, or populations require priority action or investment.

As such, while the conceptual definitions may differ, in practice, vulnerability assessments and risk assessments provide a similar function: they inform decisionmaking by identifying the factors that make certain systems more or less susceptible to harm from specific hazards. For the purposes of this guidance document, these terms can be used interchangeably when discussing the process of evaluating stormwater system susceptibility and informing resilience or adaptation strategies.

Part 2: Selecting An Approach

This section is designed to walk agencies through the process of selecting the most appropriate vulnerability assessment approach for your agency's needs. Drawing on lessons from the literature and real-world agency experience, the guidance is organized as a series of steps, that comprise a practical, decision-focused roadmap. Before getting into the details, Box 2 provides an overview of how to use this section.

Box 2. Guidance for Selecting an Approach

- **Step 1: Clarify Your Purpose**
 - Start by defining the primary goal of your vulnerability assessment. Are you aiming to meet regulatory requirements, inform long-term adaptation planning, prioritize investments, or communicate with stakeholders? The intended use will shape the level of detail and type of outputs you need.
- **Step 2: Assess Your Resources and Timeline**
 - Evaluate your agency’s available staff, technical expertise, funding, data, and time. This will help you determine which approaches are feasible and how ambitious your assessment can be.
- **Step 3: Select the Approach (or Mix of Approaches)**
 - Use the decision tree provided to match your purpose and resources to specific assessment methods—ranging from foundational, qualitative approaches to advanced, quantitative analyses. Consider whether you need asset-specific or category-based outputs, and whether a blended or layered approach may offer the best information to support decisionmaking.
- **Step 4: Document and Communicate Your Choices**
 - As you move through each step, document your rationale for selecting particular methods. This will support transparency, facilitate communication with stakeholders, and ensure your assessment is defensible and actionable.

Step 1: Clarify the Purpose

Begin by determining the primary goal of your vulnerability assessment. If the primary purpose is compliance with regulatory requirements—such as producing a FEMA Hazard Mitigation Plan (HMP) or qualifying for mitigation grants—agencies should favor approaches that prioritize standardized exposure and sensitivity analyses (e.g., using expert judgement, scorecards, or basic spatial overlays with public data like FEMA floodplain maps). If the goal is to inform broader climate adaptation planning, such as supporting regional resilience strategies or sustainability objectives, a more involved approach may be warranted. These may incorporate exposure, sensitivity, and adaptive capacity; integrate climate projections; and address multiple hazards and compounding risks—methods can range from indicators and spatial analysis to modeling. When the focus is on identifying investment priorities or vulnerable subpopulations, the assessment may need to drill down into sensitivity by asset type, function, or community—thereby requiring more detailed spatial or indicator-based assessments. The scope of hazards should also be established; agencies addressing a range of climate threats (e.g., flooding, sea-level rise, extreme heat) may need more comprehensive and integrative approaches.

More specifically, it is important to correctly scope the level of detail needed for a given purpose. To do so, we offer two main categories—*asset-specific vulnerability* or *category-based vulnerability*—which differ by their level of granularity. These terms are defined below and summarized in Table 2. Examples of the application of each of these outputs are also included in Table 2. Agencies should think critically about exactly what the vulnerability assessment will inform, as well as the level of detail needed to ensure investments in these assessments are necessary and targeted.

Asset-specific and *category-based* vulnerability assessments are related but serve different purposes. Asset-specific assessments work at the micro level, naming and characterizing individual assets—allowing for precise intervention. Category-based assessments operate at the

“macro” level, summarizing conditions for groups of assets or broader areas. Asset-specific assessments are best suited for targeted upgrades, maintenance planning, or demonstrating regulatory compliance for individual facilities, and typically draw on detailed, site-specific data such as engineering inspections, asset condition surveys, or facility-level hazard maps. In contrast, category-based assessments are most useful for strategic resource allocation, public communication, identifying system-wide patterns, or meeting mandates for area-wide planning, and often rely on aggregated data sources such as census demographics, land use classifications, infrastructure age profiles, or modeled hazard exposure for general asset types or geographic units. This means category-based methods can be applied even when inventories of individual assets are incomplete, unavailable, or impractical to collect. Finally, some agencies may need both approaches at different times and for different uses.

Table 2. Vulnerability Assessment Output

	Key Features	Example Use			
		Planning	HMPs	Communication, Engagement	Regulatory Compliance
Asset-Specific Vulnerability	<ul style="list-style-type: none"> • Focuses on individual, named assets • Provides detailed, location-specific information • Supports targeted interventions for the most at-risk assets 	Deciding which specific retention ponds or stormwater outfalls require immediate maintenance or upgrades in the next capital improvement cycle.	Identifying the most at-risk pumping stations or critical infrastructure to prioritize for retrofitting or relocation in the HMP.	Informing residents or facility managers about the vulnerability of their specific property or asset, and engaging them in risk reduction actions.	Demonstrating to regulators that specific assets (e.g., a particular outfall) meet or fail to meet required flood protection standards.
Category-Based Vulnerability	<ul style="list-style-type: none"> • Focuses on categories of assets or broader geographic units • Provides generalized, system-wide or area-wide insights • Supports strategic planning and prioritization at the system or community level 	Allocating resources or prioritizing investments to neighborhoods or asset categories (e.g., all residential areas in floodplains) that are most at risk.	Identifying neighborhoods or asset categories (e.g., all older retention ponds) that are generally more vulnerable, to guide area-wide mitigation strategies.	Sharing vulnerability maps or summaries with the public or stakeholders to raise awareness about which communities or asset categories are most at risk, fostering collective action.	Demonstrating compliance with regulations that require system-wide or area-wide assessments of vulnerability, rather than asset-by-asset reporting.

Asset-Specific Vulnerability

Asset-specific vulnerability refers to the assessment of vulnerability for individual, identifiable assets within a stormwater system. This approach evaluates the vulnerability of each specific asset—such as a particular pumping station, retention pond, or household—based on its unique characteristics, location, condition, and exposure to hazards (e.g., flooding, equipment failure). Examples of this type of output include:

- A system-wide assessment of all pumping stations identifies Pumping Station A at 123 Main Street as highly vulnerable to flooding due to its low elevation and proximity to a river, while Pumping Station B at 456 Oak Avenue is less vulnerable because it is on higher ground and has recently upgraded flood barriers.
- An evaluation of all retention ponds in the municipality finds that Retention Pond #7 is at risk of overflow during a 10-year storm event due to limited storage capacity, whereas Retention Pond #3 has sufficient capacity and is less vulnerable.
- A citywide analysis of residential properties determines that Household 101 on Elm Street is highly vulnerable to basement flooding because of poor drainage and a history of water intrusion, while Household 202 on Maple Avenue is not.
- A comprehensive inventory of stormwater outfalls reveals that several specific outfalls are at high risk of blockage or backflow during heavy rainfall events, while others are less exposed due to recent maintenance or favorable locations.
- A utility-wide survey of critical facilities (e.g., pump houses, control centers) produces a ranked list of assets by vulnerability, supporting targeted investments in the most at-risk locations.

Figure 2. Example Asset-Specific Vulnerability Assessment



SOURCE: Reproduced from Southern California Regional Rail Authority, 2022, p. 16. Used with permission.

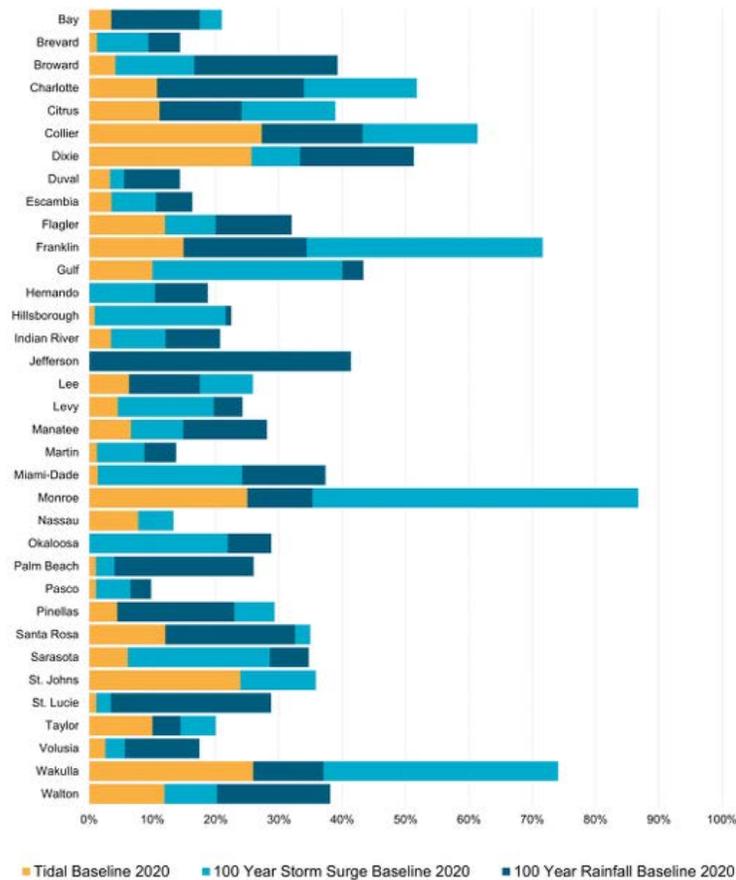
NOTES: Example site-level flood vulnerability assessment for Metrolink rail infrastructure along a portion of the San Gabriel Subdivision in Southern California, showing track conditions and flooding influence from the Cucamonga Channel. The effort demonstrates how asset-level data can be leveraged to evaluate flood hazard exposure and inform strategies, including nature-based solutions, within the Metrolink right-of-way.

Category-based Vulnerability

Category-based vulnerability refers to the assessment of vulnerability for groups or categories of assets, or for broader geographic areas, rather than for individual assets. This approach aggregates vulnerability information to provide insights into which types of assets (e.g., all retention ponds), asset classes, or general locations (e.g., neighborhoods, districts) are most vulnerable within the stormwater system. Examples include:

- Neighborhood X is identified as having a higher overall vulnerability to stormwater flooding compared to Neighborhood Y, based on aggregated data on asset conditions, land use, and historical flood events.
- An analysis of all stormwater outfalls by type (e.g., gravity-fed vs. pumped) reveals that gravity-fed outfalls are generally more susceptible to backflow during extreme rainfall events, guiding system-wide upgrades.
- A citywide review of commercial properties shows that shopping centers and industrial parks, as asset categories, are more exposed to surface flooding than schools or hospitals, informing future zoning and development policies.
- District-level vulnerability mapping highlights that eastern districts, as a group, face greater risk from combined sewer overflows due to older infrastructure and higher impervious surface coverage.
- A comparison of asset classes finds that green infrastructure installations (e.g., bioswales, rain gardens) are less vulnerable to system overload than traditional gray infrastructure, supporting expansion of nature-based solutions.
- A summary report ranks all neighborhoods in the municipality by their average vulnerability score, helping prioritize stakeholder engagement and adaptation funding.

Figure 3. Example Category-Based Vulnerability Assessment



SOURCE: Reproduced from Florida Department of Environmental Protection, 2024, p. 32. Used with permission.
 NOTES: Example of a category-based vulnerability assessment showing the percentage of transportation assets at risk of being impacted by tidal flooding, 100-year storm surge, and 100-year rainfall events in Florida’s coastal counties. Vulnerability is aggregated by county across all transportation asset types and exposure estimated as presence in each floodplain, providing system-wide insights to support regional prioritization, resource allocation, and area-wide adaptation planning.

Step 2: Assess Available Time and Resources

Evaluate your agency’s institutional capacity, funding, access to data, and technical expertise. Agencies with limited staff or data availability may be best served by simpler approaches using expert judgement, scorecards, or readily accessible indicator data. Regional partnerships or existing studies can help offset resource gaps for foundational approaches. Moderate capacity (e.g., some GIS/data staff, mid-level funding) allows for integration of spatial analyses and the use of proxy indicators and may include limited adaptive capacity assessment. High-capacity agencies—with experienced personnel, robust datasets (e.g., LiDAR, up-to-date infrastructure inventories), high-levels of stakeholder engagement, and dedicated funding—can pursue advanced strategies like detailed spatial modeling, scenario analysis, and multi-hazard integration. The availability of stakeholder support and the possibility of leveraging external

technical consultants should also be considered, especially for more complex or resource-intensive analyses.

Agencies should also consider as a component of their timeline and resource access how many resources could be useful for stakeholder engagement. Best practice is to meaningfully engage relevant stakeholders throughout the process. This includes individuals and organizations who will use the assessment findings, those to whom the results will be communicated, and those with meaningful equities or lived experience with vulnerabilities within the scope of the assessment. Stakeholder input helps ensure assessments are locally relevant, equitable, and actionable.

The following two sections define the categories of resource access and assessment timelines used to support selecting an approach in Step 3.

Access to Resources

High access to resources refers to agencies or jurisdictions that have ample staffing, technical expertise, funding, and data availability to support comprehensive and technically sophisticated vulnerability assessments. These organizations typically have dedicated resilience, sustainability, or planning offices, access to advanced modeling tools, robust GIS datasets, and the capacity to engage consultants or develop new qualitative or quantitative data as needed. High resource availability enables the pursuit of integrated, scenario-based, spatially detailed assessments, covering multiple hazards and including extensive stakeholder engagement, ultimately supporting the development of comprehensive strategic plans and detailed adaptation strategies.

Moderate access to resources describes agencies with a reasonable but not unlimited level of capacity—such as dedicated staff for vulnerability or hazard analysis, access to state or regional datasets and mapping tools, and some funding for technical support or consultation. These organizations can implement intermediate assessments, such as block-level or functional spatial analysis, combine proxy indicators with available data, and conduct meaningful though less detailed adaptive capacity assessments. Collaboration with neighboring jurisdictions or regional partnerships is common for moderate-resource settings.

Low access to resources characterizes agencies with limited staffing (often only part-time personnel focused on vulnerability or resilience), little or no dedicated funding for comprehensive studies, and reliance on publicly available or legacy data (e.g., FEMA floodplain maps, basic asset inventories). Assessments in these circumstances are typically foundational, relying heavily on expert judgement, qualitative approaches, stakeholder workshops, or simple overlays of publicly available maps, and often focus primarily on regulatory compliance or meeting minimum hazard mitigation planning requirements

Assessment Timelines

Short-term refers to vulnerability assessment that is completed in a few weeks to a few months. This timeframe often aligns with foundational approaches such as expert judgement, qualitative scorecards, and basic overlays using available hazard and asset data. These are commonly used when staff time and resources are limited, and the primary need is to meet regulatory compliance or deliver rapid, preliminary findings.

Medium-term refers to a vulnerability assessment conducted over several months up to approximately a year. This timeline supports intermediate approaches that combine spatial analyses, proxy indicators, with moderate data collection and analysis efforts. Medium-term assessments enable agencies to address multi-hazard risks, incorporate some adaptive capacity considerations, and support decisionmaking for investment and adaptation planning beyond minimum compliance.

Long-term vulnerability assessment lasting one or more years, often organized as a multi-year effort. This duration allows for advanced approaches such as detailed modeling, scenario-based analyses and new data acquisition. Longer-term assessments underpin strategic, comprehensive adaptation planning and can address a range of hazards, social vulnerability, and system-wide impacts, making them suitable for agencies with high capacity and resources.

Step 3: Select the Approach

Once you have clarified the purpose of your vulnerability assessment and assessed your available resources, you can select the most appropriate approach—or combination of approaches—for your agency’s needs. The decision tree in Figures 4 and 5 guides stormwater agencies through key considerations for selecting vulnerability assessment approaches. Drawing from Steps 1 and 2 in this guide, follow the flow of the decision tree based on the level of detail you need (category-based in Figure 4 and asset-specific in Figure 5), assessment timelines and access to resources, recognizing you may pursue different approaches or combine methods for a comprehensive assessment. Definitions for the terms in the decision tree are provided in the prior section on selecting an approach. The following additional considerations may factor into your choices in the decision tree:

- **Data Availability:** Are spatial, demographic, or asset-level data sufficient for analysis?
- **Technical Capacity:** Is GIS/modelling expertise available in-house or via partners?
- **Stakeholder Engagement:** Is there a need for participatory/inclusive input? Include in consideration of timeline.
- **Regulatory Requirements:** Are there specific standards or benchmarks to meet? Include in consideration of level of detail needed.
- **Intended Use:** Screening/prioritization, or detailed capital planning/regulatory justification.

Best Practices for Layering Approaches

Layering approaches in vulnerability assessment refers to starting with simple, resource-efficient methods such as expert judgement or scorecards to quickly identify priorities and gaps, then applying more advanced techniques—like spatial analysis, modeling, or in-depth expert judgement—as data, time, and resources allow. This sequence allows agencies to build on initial findings, incorporate increasingly complex data and analyses, and refine recommendations over time. For example, an agency may use a more limited qualitative assessment for initial screening, then add spatial overlays and indicator analysis for targeted assets and finally develop detailed modeling with expert judgement validation for the most at-risk locations.

1. Begin with readily available data and simple tools (e.g., overlays of public hazard maps, qualitative scorecards), especially if resources or timeline are limited.
2. As capacity and data improve, integrate spatial analysis to examine geographic patterns and asset clustering.
3. For areas requiring deeper insight, use quantitative indicators and, where technically feasible, modeling to capture system dynamics and possible future changes.
4. Incorporate expert judgement throughout, especially to validate findings and fill gaps in data. As a part of expert judgement, consider stakeholder engagement as a layer, using workshops or participatory mapping in tandem with technical analysis to ensure findings are actionable and locally relevant.
5. Match analysis detail and complexity to project goals—e.g., compliance efforts may not need high-resolution modeling, whereas climate adaptation planning benefits from scenario-based analysis and multi-hazard integration.
6. Document each assessment phase and rationale for methodology choice to ensure transparency for regulators, funders, and community stakeholders.

Addressing Early-Stage Gaps and Errors in Layered Approaches

While layering methods offers an efficient, iterative path toward increasingly detailed vulnerability assessments, agencies should also recognize that early qualitative or simplified analyses may contain gaps, biases, or inaccuracies that could influence subsequent results. When transitioning to more resource-intensive approaches, it is critical to incorporate a validation step before layering new analyses onto earlier findings.

Validation can include cross-checking initial results against available quantitative data, conducting stakeholder or peer reviews, or running targeted “spot checks” on high-priority areas. If significant errors or missing information are discovered—for example, if earlier expert judgement incorrectly identified vulnerable assets or mischaracterized exposure patterns—it may be preferable to revisit or re-do those foundational steps rather than simply layering new analyses.

Whether to “start over” versus “build upon” depends on the extent and nature of the discrepancies. Minor or localized gaps can typically be corrected through validation, refinement, or sensitivity testing in updated analyses. Systemic or conceptual errors—such as mis-defined system boundaries, misunderstood hazard mechanisms, or inconsistent data—usually warrant

re-scoping or restarting the assessment. A practical rule of thumb is to assess whether the underlying inputs, assumptions, and definitions used in the initial approach remain sound and fit for the next level of analysis. If they are not, subsequent layers should use corrected or newly verified baselines rather than relying on earlier outputs.

How to Use the Decision Tree for Layering Methods

The decision tree in Figures 4 and 5 can be applied more than once over the life of a vulnerability assessment to reflect evolving goals, resources, and data availability. Agencies may begin with an initial purpose that is constrained by time or resources, which will guide them toward a less resource- and time-intensive path in the tree (e.g., expert judgement, scorecards, or basic spatial overlays). As additional capacity, data, or stakeholder input becomes available, the agency can revisit the decision tree with a more detailed, longer-term purpose in mind. This second pass may lead to more technically complex approaches — such as spatial analysis, indicator development, or modeling — that build upon earlier findings.

Figure 4. Decision Tree – Plan and Communicate by Asset Category or Geographic Area

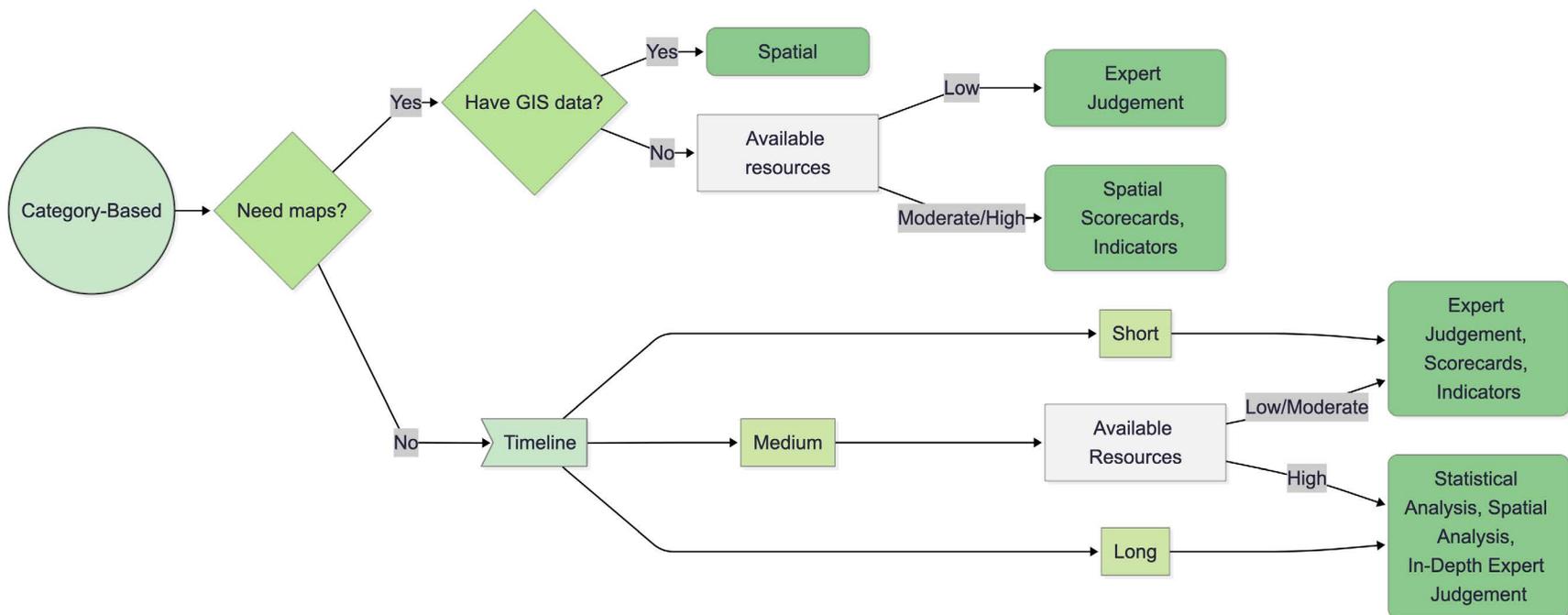
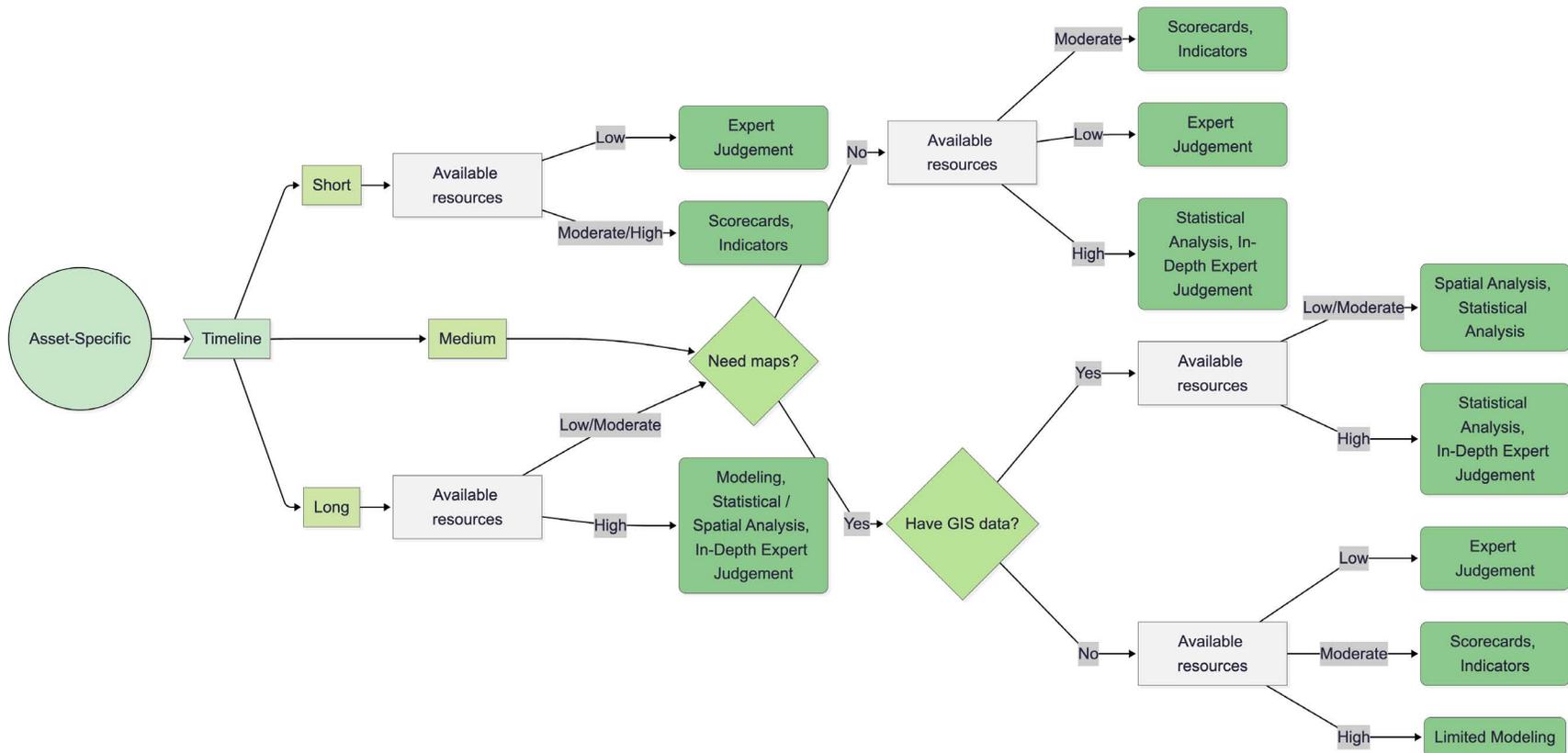


Figure 5. Decision Tree – Act at Individual Asset Level



After selecting an initial path through the decision tree, agencies may find it useful to revisit their choices with a more detailed understanding of each approach’s relative advantages and limitations. Table 3 summarizes the major trade-offs among commonly used vulnerability-assessment methods—including how resource demands, data needs, and analysis depth influence the type of information produced. Use this table to verify that the selected method (or combination of methods) aligns with your intended timeline, needs and technical capacity.

Table 3. Tradeoffs Across Vulnerability Assessment Approaches

Approach	Advantages	Limitations	Timeline
Expert Judgment	<ul style="list-style-type: none"> • Flexible—can be implemented rapidly or extensively depending on available time and stakeholder participation. • Captures rich local and experiential knowledge often missing from data-driven methods. • Builds internal and cross-sector ownership of findings. • Valuable for scoping, prioritization, and contextualizing results from other approaches. 	<ul style="list-style-type: none"> • Highly dependent on participant expertise and diversity; potential bias if perspectives are narrow. • Limited transparency and repeatability without structured documentation. • Quantification is subjective unless combined with scoring or indicator data. 	<ul style="list-style-type: none"> • Streamlined: 2–6 weeks for focused workshops/interviews. • In-depth: 3–12 months if iterative consultation and multi-sector engagement are included.
Scorecards	<ul style="list-style-type: none"> • Provides semi-quantitative structure for expert and stakeholder input; supports transparent scoring of exposure, sensitivity, adaptive capacity. • Useful for prioritization under limited data availability. • Easy to communicate results internally and externally. 	<ul style="list-style-type: none"> • Subjectivity can still dominate scoring if criteria are not well-defined. • Can oversimplify complex system interactions. • Requires careful facilitation to avoid “false precision” in the ratings. 	<ul style="list-style-type: none"> • Streamlined: 2–4 months for focused staff-led scoring. • In-depth: 6–12 months if multi-round workshops, validation, and scoring of many assets/categories are included.
Indicators	<ul style="list-style-type: none"> • Creates consistency and comparability across areas using measurable variables. • Enables semi-quantitative analysis that balances data and local context. • Useful foundation for mapping and aggregation. 	<ul style="list-style-type: none"> • Data quality may vary across indicators. • Proxy measures may not fully represent adaptive capacity or functional linkages. • Risk of losing nuance if indicators are aggregated mechanically. 	<ul style="list-style-type: none"> • Typically 3–9 months depending on data gathering and validation needs.
Spatial Analysis	<ul style="list-style-type: none"> • Strong visual products; highly intuitive for communication and decision-making. • Enables clear identification of exposure “hotspots” and spatial patterns. • Integrates with most other approaches and supports multi-hazard analysis. 	<ul style="list-style-type: none"> • Requires sufficient geospatial data quality and analytic skill. • Often limited to exposure and partial sensitivity; adaptive capacity data may not be spatially explicit. • Results depend on resolution and accuracy of hazard layers. 	<ul style="list-style-type: none"> • Basic overlays: 2–4 months. • Comprehensive spatial modeling with validation: 6–18 months.
Statistical Analysis	<ul style="list-style-type: none"> • Generates quantitative estimates of probability, severity, and potential losses. • Useful for calibration, validation, and grant eligibility documentation. • Can reveal trends and changes over time. 	<ul style="list-style-type: none"> • Dependent on historical datasets. • Often retrospective; may underrepresent future climate-driven changes unless projections are included. • Requires technical expertise and quality-control. 	<ul style="list-style-type: none"> • Typical range: 6–12 months, longer if scenario analyses or cross-sector data integration are needed.

Modeling

- Highest technical detail—supports scenario-based planning and design-level decisionmaking.
- Integrates exposure and sensitivity quantitatively; can test adaptation measures.
- Produces results suitable for regulatory and infrastructure investment contexts.
- Resource-intensive; requires substantial data and expert capacity.
- May exclude social or institutional dimensions unless explicitly modeled.
- Can be difficult for smaller agencies to sustain or replicate independently.
- Typically 12–24 months depending on model complexity, calibration, and stakeholder engagement.

Step 4: Document and Communicate Your Choices

Using Table 4 below, complete each section alongside the steps in the guidebook. Share the worksheet with stakeholders and decisionmakers to support transparency and facilitate feedback. The sections on stakeholder engagement and communication products are optional but may be useful as agencies think through the intended purpose and use of the vulnerability assessment or document its process.

Table 4. Vulnerability Assessment Worksheet

Section	Item/Prompt	Response/Notes
Agency Information	Agency Name	
	Assessment Title/Project	
	Date	
	Lead Staff/Contact	
Assessment Purpose	Primary Goal(s)	(e.g., regulatory compliance, capital planning, climate adaptation, stakeholder engagement)
	Intended Use of Results	(e.g., inform investment decisions, support grant applications, guide operational changes)
	Key Stakeholders	(e.g., internal departments, community groups, regulatory agencies)
Scope & Level of Detail	System Elements Assessed	(e.g., assets, functions, populations, environmental features)

Hazards Considered (e.g., flooding, extreme heat, drought, infrastructure failure)

Level of Granularity Asset-specific Category-based Both

Geographic Extent (e.g., citywide, district, watershed, facility-level)

Resources & Timeline

Staffing and Expertise (e.g., in-house GIS, external consultants, stakeholder panels)

Data Availability (e.g., asset inventories, hazard maps, demographic data)

Funding/Budget (e.g., grant sources, internal allocations)

Timeline Short-term Medium-term Long-term

Selected Approaches

Method/Tool Check all that apply for each aspect of vulnerability

Expert Judgement Exposure Sensitivity Adaptive Capacity

Scorecards	<input type="checkbox"/> Exposure <input type="checkbox"/> Sensitivity <input type="checkbox"/> Adaptive Capacity
Indicators	<input type="checkbox"/> Exposure <input type="checkbox"/> Sensitivity <input type="checkbox"/> Adaptive Capacity
Spatial Analysis	<input type="checkbox"/> Exposure <input type="checkbox"/> Sensitivity <input type="checkbox"/> Adaptive Capacity
Statistical Analysis	<input type="checkbox"/> Exposure <input type="checkbox"/> Sensitivity <input type="checkbox"/> Adaptive Capacity
Modeling	<input type="checkbox"/> Exposure <input type="checkbox"/> Sensitivity <input type="checkbox"/> Adaptive Capacity
Other (specify)	

Blended/Layered Strategy	Describe layered approach
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Rationale for Selection	Describe rationale
-------------------------	--------------------

Stakeholder Engagement	Engagement Activities (e.g., workshops, surveys, advisory committees)
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Key Input Received	Summarize major feedback or concerns
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How Input Was Incorporated Describe changes or decisions made based on stakeholder input

Communication Products Planned Outputs (e.g., maps, summary reports, dashboards, presentations)

Intended Audiences (e.g., technical staff, elected officials, public, regulators)

Key Messages Summarize main findings and recommendations

Part 3: Carrying Out a Vulnerability Assessment

In Part 2, we provided an overview of how to select an approach for a vulnerability assessment. This section provides more details on how to inform and implement that choice, as well as next steps to carry out the whole of the vulnerability assessment. *Defining the Purpose of Your Vulnerability Assessment* provides more detail on the different uses of vulnerability assessments that can help inform agency decisionmaking related to the purpose of their vulnerability assessment. *Implementing Vulnerability Assessment Approaches* describes each approach in more detail, along with examples of those approaches in practice. The final section in Part 3, *A Step-by-Step Framework for Conducting Vulnerability Assessments*, outlines how agencies could carry out the entire vulnerability assessment.

Defining the Purpose of Your Vulnerability Assessment

Stormwater agencies, along with municipalities, counties, states, and other governmental partners, utilize vulnerability assessments across a range of practical contexts. These applications extend beyond traditional planning and hazard mitigation—vulnerability assessments can support regulatory compliance, public communication, land use and capital investment decisions, and multi-jurisdictional coordination. Agencies may leverage these assessments to fulfill federal or state grant requirements, inform stormwater system upgrades, engage stakeholders, or document progress toward climate resilience goals. As detailed in Part 2, clearly identifying the intended uses of an assessment is a foundational first step that shapes its scope, methods, and resource needs. The following sections can help agencies understand, in more detail, various uses of vulnerability assessments in practice.

Planning

Vulnerability assessments are most commonly used to inform a variety of planning activities relevant to stormwater agencies and their partners. These assessments provide the analytical foundation for infrastructure planning, land use decisions, climate adaptation strategies, and comprehensive resilience initiatives.

For infrastructure planning, vulnerability assessments typically identify which assets—such as stormwater systems, transportation networks, and utilities—are most at risk from hazards like flooding, sea-level rise, and extreme weather. This enables agencies to prioritize upgrades, retrofits, and future investment in locations vulnerability is highest, as well as to plan for redundancy and system resilience.

In land use planning, agencies employ vulnerability assessments to integrate hazard exposure information into decisions about new development, zoning, and redevelopment priorities. Assessments provide data that could be used to steer growth away from high-risk areas and inform policies that reduce long-term risks to people, property, and vital community services.

If not integrated into the above planning processes, climate adaptation planning is another area where vulnerability assessments play a central role by providing a framework to characterize how hazards related to climate change are likely to impact assets, functions, and populations under multiple future scenarios. Similar to the land use and infrastructure applications, agencies and their partners can identify high vulnerability areas under future climate and use these to inform both near- and long-term adaptation actions, ranging from hard infrastructure interventions to nature-based solutions and social resilience strategies. One example of how a vulnerability analysis informed a climate adaptation plan is shown in Box 3, below.

Box 3. Resilient Fairfax Climate Adaptation and Resilience Plan in Fairfax County, Virginia

The Resilient Fairfax Climate Adaptation and Resilience Plan used vulnerability assessments as a foundational input for developing and prioritizing its adaptation strategies. The planning process was driven by a rigorous analysis that included the Climate Projections Report, the Vulnerability and Risk Assessment (VRA), and an Audit of Existing Policies, Plans, and Programs. The VRA identified which infrastructure types, natural resources, public services, and populations within Fairfax County were most exposed, sensitive, and least adaptive to projected climate hazards. By applying the exposure-sensitivity-adaptive capacity methodology, the county determined the top vulnerabilities by sector and system—such as identifying which stormwater infrastructure, vulnerable populations, and critical services faced the greatest threats from flooding, heat, severe storms, and other hazards.

These findings, in combination with the Audit (which highlighted where the county was already taking effective measures and where policy or program gaps remained), informed the initial list of potential adaptation strategies. The process also incorporated a review of national best practices. Collaborative workshops and engagement with stakeholders—including county departments, advisory groups, and the community—were used to refine and score strategies based on criteria such as staff and financial capacity, technical feasibility, alignment with county plans, and anticipated co-benefits.

Hazard Mitigation Planning (HMPs)

Vulnerability assessments serve as a foundational element of local and regional hazard mitigation plans. Agencies use them to identify at-risk assets (e.g., buildings, critical facilities, populations) and inform the development of actionable mitigation strategies. They are also required for eligibility for federal and state disaster grants and the National Flood Insurance Program (NFIP), and new guidance increasingly encourages the integration of climate change considerations into HMPs.

FEMA’s most recent guidance on vulnerability analyses for HMPs recommend the use of a comprehensive and systematic assessment of the jurisdictions, populations, structures (including critical facilities), infrastructure, and community lifelines that are most at risk from identified hazards (FEMA, 2025a; FEMA, 2025b). Vulnerability assessments within HMPs often follow the structure of assessing exposure, sensitivity and adaptive capacity as components of vulnerability. The analysis must specify which areas are most threatened, detailing the type, location, expected intensity, and probability of hazards, and address potential impacts to people, buildings, and essential services. Many HMPs, for example, use FEMA floodplain maps to assess the exposure of structures and populations to flood hazards. State and local plans must

also summarize potential losses. Such sensitivity assessments are often supported by tools like HAZUS, which quantify potential losses and impacts. While not always explicitly labeled as adaptive capacity, HMPs often include a capability assessment that inventories existing mitigation actions, regulatory tools, or recovery resources for each jurisdiction. Changes in development, land use, demographics, and critical infrastructure that affect vulnerability must also be incorporated into assessments supporting HMPs.

Ultimately, the completed vulnerability analysis is often integrated into problem statements or matrices that drive the selection and prioritization of mitigation actions, support funding eligibility, and be regularly revised to reflect new data, lessons learned, and stakeholder input. One example of these matrices is shown below in Box 4.

Box 4. Hampton Roads Planning District Commission, Virginia 2022 HMP

The Hampton Roads Planning District Commission (PDC) HMP directly uses the vulnerability assessment to inform the identification and prioritization of mitigation techniques. The vulnerability assessment combines quantitative methodologies, including HAZUS and GIS-based approaches, and qualitative assessments based on local knowledge to determine the exposure and sensitivity of assets, populations, and infrastructure to a range of hazards, including flooding, sea-level rise, and tropical storms. This hybrid approach allows the plan to approximate risks, estimate potential losses, identify at-risk community assets, and address uncertainties due to limitations in data and analysis.

The findings from the vulnerability assessment directly shape the selection of mitigation techniques. Specifically, the vulnerability analysis, combined with an analysis of capability, are used to identify feasible mitigation policies and projects that both reduce future hazard impacts and support economic, environmental, and social goals. Matrices of mitigation techniques are linked to hazards identified as high or moderate risk (as shown in the figure below), and the selection process considers the likely effectiveness, cost-benefit, implementation feasibility, and potential to address socially vulnerable populations. Importantly, this process does not rely on asset specific vulnerabilities and instead summarizes the vulnerability analysis to create a set a priority hazards for the region.

Each proposed mitigation action is further detailed in their Mitigation Action Plan, including which priority hazards the action addresses, as well as timelines, cost estimates, and funding sources. The prioritization of actions is guided by factors including reduction in risk to life and property, social vulnerability rankings from the National Risk Index, ease of implementation, community and political support, and economic and funding considerations.

Communication, Stakeholder Engagement and Coordination

Vulnerability analyses also play a role in communicating risk and resilience priorities to a broad audience, including the public, decision makers, partner agencies, and other stakeholders. By translating complex technical information into maps, impact summaries, and spatial visualizations, vulnerability assessments help to make abstract threats—such as future flooding or infrastructure sensitivity—tangible and relevant to community members and leaders. Data from vulnerability assessments can also demonstrate not only which areas or populations are most at risk, but also why certain mitigation or adaptation actions are proposed, building transparency in the planning process. For example, many vulnerability assessments emphasize the importance of narrative and graphical summaries, which help stakeholders and the public to understand key findings.

Vulnerability assessments also provide a structured platform for meaningful stakeholder engagement. Multi-jurisdictional or regionally coordinated vulnerability assessments, in

particular, can bring together diverse agencies (e.g., emergency management, public works, transportation, stormwater, sustainability) along with community organizations and residents. By involving varied perspectives in the process of identifying vulnerabilities and potential solutions, agencies can ensure that the results are locally relevant. Stakeholder workshops and collaborative assessment processes allow for the integration of both technical expertise and local knowledge, can highlight gaps or needs that might be missed in purely technical analyses, and create shared ownership of resilience strategies. Box 5 provides an example of an HMP with significant stakeholder engagement.

On a regional scale, joint vulnerability analyses encourage coordination across jurisdictions that may face similar hazards but have differing capacities or regulatory contexts. Regional vulnerability assessments can streamline data-sharing, reduce redundant analyses, and support the development of mutually reinforcing adaptation projects. From discussions recognized that coordinated assessments improved the integration of planning efforts, supported grant applications, and increased the overall effectiveness of resilience investments.

Box 5. 2024 Lehigh Valley, Virginia HMP

The vulnerability assessment for the 2024 Lehigh Valley Hazard Mitigation Plan (covering Lehigh and Northampton Counties, Virginia) engaged a diverse range of stakeholders, including county and municipal officials, emergency managers, planning and administrative staff, technical experts, and members of the general public. Engagement mechanisms included structured planning team meetings and workshops, completion of detailed worksheets and surveys modeled after state and federal guidance, and three rounds of public surveys distributed via social media. Municipal representatives participated through annual review meetings, direct outreach, and one-on-one technical assistance, while the public provided input on hazard concerns, preparedness, and mitigation preferences.

This broad engagement shaped the risk analysis by ensuring that local knowledge, recent experiences, and community priorities were incorporated into hazard identification and prioritization. For example, public survey results highlighted specific hazards of concern (such as floods, winter storms, and sinkholes), revealed gaps in preparedness and awareness, and identified vulnerable populations, all of which directly informed the assessment of risk and the development of targeted mitigation strategies. Feedback from stakeholders also led to the inclusion of emerging risks, adjustments to technical language for accessibility, and the prioritization of actions that addressed both community education and the needs of at-risk groups.

Regulatory Compliance

Vulnerability assessments can also support regulatory compliance for stormwater agencies, particularly for MS4 (Municipal Separate Storm Sewer System) permit requirements under the National Pollutant Discharge Elimination System (NPDES) program. These permits require agencies to develop and implement Stormwater Management Programs (SWMPs) that address public education, illicit discharge detection, runoff control, post-construction management, pollution prevention, monitoring, reporting, and in some cases, TMDL (Total Maximum Daily Load) implementation for impaired waters. An analysis of System Vulnerability Factors (SVFs), required as a part of MS4 permits, provides a partial analysis of vulnerability, focusing on system sensitivity, as described in Box 6.

In this context, vulnerability assessments can identify areas within the MS4 jurisdiction that are especially sensitive to stormwater impacts, such as flooding, erosion, or pollutant loading. Mapping vulnerability allows agencies to pinpoint high-risk subwatersheds, critical infrastructure, or neighborhoods, helping agencies comply with regulatory expectations by prioritizing and justifying the allocation of resources or enhancement of stormwater control measures. One example of this is described in Box 6, below. The results of vulnerability assessments can also inform the adoption of Best Management Practices (BMPs), often included in SWMPs. As regulatory standards place increasing emphasis on climate resilience, vulnerability assessments are becoming even more important for evaluating future risks from changing rainfall patterns or sea level rise and for planning adaptive measures that ensure compliance over long time horizons.

Box 6. Town of Millis, Massachusetts Stormwater Management Program

In the SWMP for the Town of Millis, vulnerability factors—specifically referred to as System Vulnerability Factors (SVFs)—are used to inform and prioritize SWMP activities. The MS4 permit requires the town to assess all drainage catchments for the presence of SVFs that could indicate a heightened risk for illicit connections and pollution. SVFs are based on a GIS analysis of a range of factors, including sanitary sewer overflows, common manholes and trench construction, sewer alignments with underdrains, infrastructure defects, and a history of combined sewers, aging infrastructure and frequent septic system failures. The analysis was based on historical records and field inspections and focused primarily on system sensitivity, rather than exposure.

SVFs helped the town identify where enhanced wet weather sampling and investigations are necessary. Outfalls that have one or more critical SVFs were prioritized for field investigations and additional water quality monitoring. The vulnerability analysis also helped shape decisions regarding the implementation of Best Management Practices (BMPs), informed the prioritization of maintenance and infrastructure upgrades, and guided the selection of specific outreach and education initiatives.

Implementing Vulnerability Assessment Approaches

Expert Judgement

Expert judgement is a foundational approach for stormwater vulnerability assessment, often serving as the starting point when technical or data resources are limited. This method draws on the practical experience and local knowledge of professionals such as city engineers, stormwater managers, emergency responders, and public works staff, or, importantly, from community members with lived experiences of vulnerabilities in their neighborhoods. Through structured engagement, often in the form of workshops or the formation of an expert panel, these experts help identify which system components (e.g., pump stations, outfalls, neighborhoods) are most exposed to hazards, which are most sensitive to impacts, and where adaptive capacity exists or is lacking.

In practice, the expert judgement approach is seen in many HMPs that fulfill baseline requirements for compliance and grant eligibility, as well as a part of more comprehensive

vulnerability assessments. These expert-based assessments often produce narrative summaries and priority rankings based on the expert panel’s consensus, informing the development of action items or further technical studies. While well-suited to getting diverse perspectives integrated and generating actionable insights when technical barriers exist, this approach is limited in its ability to capture system complexity or provide defensible, replicable results for comparison or tracking progress over time. Expert judgement also highly depends on the expertise and experience of those included as experts in the process. Adaptive capacity considerations, in particular, are typically mentioned in passing or omitted due to a lack of concrete data or methods for systematic evaluation.

Implementation Guidance

Agencies using expert judgement for some or all of their vulnerability assessment could consider the following options.

- Targeted interviews: Interviews with key staff who manage or maintain stormwater infrastructure. Ask specific questions about recent flooding events, known problem areas, asset conditions, and operational challenges. For example:
 - “Which pump stations have experienced repeated failures during heavy rainfall?”
 - “Are there neighborhoods that consistently report basement flooding?”
- Small group discussions or focus groups: Bring together a handful of stormwater engineers, maintenance supervisors, and emergency managers to discuss system vulnerabilities. Use maps or asset lists to prompt discussion about exposure (e.g., low-lying areas, aging infrastructure), sensitivity (e.g., critical facilities, high-risk neighborhoods), and adaptive capacity (e.g., backup pumps, emergency response protocols).
- Workshop-based mapping exercises: A workshop where participants annotate maps of the stormwater system, marking locations of frequent flooding, infrastructure bottlenecks, or areas with limited redundancy. This visual approach helps experts collectively identify and prioritize vulnerabilities. This can also be used to validate or update existing flood or other hazard maps.
- Review of incident reports and maintenance logs: Ask experts to interpret patterns in historical incident data, such as service requests, emergency repairs, or flood damage reports. Their insights can help validate or supplement findings from other assessment methods.
- Consensus ranking: A process where experts rank assets or neighborhoods by perceived vulnerability, using simple scorecards or voting. This can help agencies quickly identify priority areas for further investigation or investment.

As agencies apply expert judgement in a stormwater vulnerability assessment, it is important to frame questions and discussions around specific system elements and recent events rather than general hazards. Being more targeted helps ensure that expert insights are grounded in operational realities and local experience. Agencies should also document not only the conclusions reached, but the reasoning and evidence provided by experts—for example, noting

that a particular pump station is considered vulnerable due to its low elevation and history of overflow incidents. Additionally, it is essential to acknowledge where expert judgement is being used to fill gaps in available data, and to flag these areas for future quantitative analysis if resources permit.

Vulnerability Assessment Team

An expert judgment assessment benefits from a team with a mix of technical and experiential knowledge. Agencies should engage staff who work directly with stormwater infrastructure—such as engineers, field supervisors, emergency management personnel, and maintenance crews—alongside planners and community representatives who understand local conditions and impacts. Including participants with lived experience of flooding or infrastructure failure can help ground discussions in real-world context. A small team is generally sufficient, but they may need additional facilitation support for workshops or interviews to ensure balanced input and documentation of consensus findings.

Expert Judgement in Practice

In Baltimore’s HMP, expert judgement was used to identify stormwater vulnerabilities by convening an advisory committee of engineers, planners, and community representatives. The committee reviewed historical flooding data, mapped problem areas, and discussed the impacts of climate change on future stormwater risks. Their input informed the prioritization of infrastructure upgrades and the development of targeted mitigation actions, while also highlighting gaps for future data collection and analysis.

Scorecards

Scorecards are structured tools that formalize expert and stakeholder input into a transparent rating system, allowing agencies to assess stormwater system vulnerabilities in a consistent, semi-quantitative manner. Typically, agencies develop rating schemes—such as scales from 1 to 5—to evaluate system components (e.g., pump stations, outfalls, neighborhoods) or geographic areas across key factors: exposure, sensitivity, and adaptive capacity. For example, a pump station might be scored for its likelihood of flooding, the consequences of failure, and the availability of backup power or alternative drainage routes.

Scorecards are often developed collaboratively, involving staff from emergency management, planning, public works, and other relevant departments. This participatory approach helps ensure that ratings reflect a broad range of operational and community perspectives, and fosters buy-in for subsequent action planning.

While scorecards are adaptable and useful when data is limited, they are inherently subjective and may oversimplify complex vulnerabilities. Exposure and sensitivity are usually addressed directly through scores for hazard likelihood and impact, while adaptive capacity may be included as a separate criterion (e.g., “ease of service restoration after disruption”), but is often

less rigorously evaluated. As such, scorecards are best suited for initial screening, prioritization, and stakeholder engagement, rather than for detailed or spatially-explicit analysis.

Implementation Guidance

Agencies using scorecards for some or all of their vulnerability assessment could consider the following options.

- **Component rating workshops:** Convene a group of stormwater engineers, planners, and maintenance staff to collaboratively rate system components (e.g., pipes, pump stations, flood-prone areas) on exposure, sensitivity, and adaptive capacity. Use a simple scale (e.g., 0–4 or 1–5) and provide qualitative justifications for each score.
- **Stakeholder surveys:** Distribute scorecard templates to a wider group of stakeholders, asking them to rate specific assets or neighborhoods based on their experience and knowledge. Aggregate responses to identify consensus and outliers.
- **Matrix development:** A matrix listing system elements along one axis and vulnerability criteria (exposure, sensitivity, adaptive capacity) along the other. Fill in scores and comments collaboratively, then use the matrix to identify priority areas for further analysis or action.
- **Scenario-based scoring:** Participants rate system components under different hazard scenarios (e.g., current conditions vs. projected mid-century climate), helping to capture changing vulnerabilities over time.

As they implement scorecards in a vulnerability assessment, agencies should additionally consider the importance of transparency and clarity in their scoring process. Clearly defining the criteria for each score and providing guidance on how to interpret the scale will help ensure consistency across participants. It is essential to document the rationale behind each score, including any supporting data, historical incidents, or operational experience that informed the ratings. Agencies should also acknowledge the inherent subjectivity of scorecard approaches and, where possible, supplement qualitative scores with available quantitative data or mapping to strengthen findings. Finally, scorecards are most effective when used as a tool for initial screening and to facilitate dialogue among stakeholders, rather than as the sole basis for detailed planning or regulatory compliance.

Vulnerability Assessment Team

Scorecard-based assessments can benefit from a collaborative team that combines technical expertise with operational and community perspectives. Participants could include stormwater engineers, public works and planning staff, and emergency management professionals familiar with hazards and asset conditions. The team may also include community representatives to provide insights on neighborhood-level impacts and resilience. A facilitator or data analyst can help maintain consistency in scoring and ensure transparency in how criteria are defined and applied.

Scorecards in Practice

In Toledo, OH, the vulnerability assessment—part of a GLISA pilot project—used scorecards to evaluate a representative set of stormwater system components, including pipes, maintenance practices, and flood-prone areas. Experts rated each component’s sensitivity and adaptive capacity on a scale of 0–4, informed by qualitative understanding of exposure and climate projections. Each score was accompanied by a written justification, reflecting expert opinion on how climate change would affect the component and its ability to accommodate projected changes. This approach enabled the city to quickly identify priority vulnerabilities and inform future planning, while also highlighting areas for further data collection and analysis.

Vulnerability Indicators

Vulnerability indicators offer a semi-quantitative approach to stormwater vulnerability assessment by using specific, measurable variables as proxies for exposure, sensitivity, and, where feasible, adaptive capacity. Common examples include percent impervious surface (as a proxy for flood risk), infrastructure age (as an indicator of sensitivity to damage), and social vulnerability indices (as a measure of community adaptive capacity), often the latter are available from state and federal agencies. By applying consistent metrics across multiple areas or assets, agencies can standardize their assessment and more easily compare vulnerabilities within and across jurisdictions.

Indicators are typically selected based on the availability and quality of local data, their relevance to stormwater management challenges, and their alignment with broader resilience or hazard mitigation frameworks. This approach allows agencies to capture variations in exposure and sensitivity with greater granularity than purely qualitative methods, supporting more targeted prioritization and resource allocation.

However, the indicator-based approach has limitations. Adaptive capacity is often represented by a narrow set of variables—such as access to vehicles, presence of backup infrastructure, or proximity to emergency services—without fully accounting for the complex social, economic, and institutional factors that shape a community’s ability to cope with or recover from hazards. As a result, indicator scores may oversimplify adaptive capacity and should be interpreted with caution.

Agencies frequently aggregate indicator scores to identify priority planning areas, vulnerable system elements, or neighborhoods in need of further intervention or detailed study. This aggregation can support the development of vulnerability maps, dashboards, or summary reports that inform decision-making and stakeholder engagement.

Implementation Guidance

Agencies using vulnerability indicators for stormwater assessments could consider the following options:

- Indicator selection workshops: Convene technical staff and local experts to identify and select relevant indicators for exposure, sensitivity, and adaptive capacity. Prioritize variables that are locally meaningful and supported by reliable data.
- Data compilation and mapping: Collect and organize indicator data for all system components or geographic areas. Use GIS or other mapping tools to visualize spatial patterns and identify clusters of vulnerability that can be represented as spatially-explicit indicators (i.e., density of critical facilities, percent impervious surface by census tract).
- Composite scoring: A scoring system that aggregates multiple indicators into a single vulnerability score for each asset or area. Clearly define how each indicator contributes to the overall score.
- Threshold analysis: Thresholds for key indicators (e.g., percent impervious surface above 50%) to flag areas for further investigation or immediate action.
- Integration with other approaches: Combine indicator analysis with expert judgement or scorecards to validate findings and address gaps in adaptive capacity assessment.

As agencies implement indicator-based assessments, they should ensure transparency in indicator selection and scoring, document the rationale for chosen variables, and acknowledge the limitations of proxy measures—especially for adaptive capacity. Where possible, supplement indicator analysis with qualitative insights or additional data sources to provide a more comprehensive understanding of vulnerability.

Vulnerability Assessment Team

Implementing an indicator-based approach requires staff with data management and GIS skills, if indicator development is intended to be spatial, supported by domain experts who can interpret indicator relevance for stormwater vulnerability. A core team might include planners, engineers, and analysts capable of sourcing, cleaning, and mapping local datasets, with input from emergency management and community members. Collaboration with regional or academic partners may be valuable for developing composite scores or integrating social vulnerability metrics that extend beyond physical infrastructure.

Vulnerability Indicators in Practice

The integrated vulnerability assessment for Oxford and Talbot County, MD, demonstrates the use of block-level social and structural indicators to inform adaptation priorities and policy guidance. The assessment team selected indicators such as percent impervious surface, infrastructure age, and social vulnerability index to evaluate exposure, sensitivity, and adaptive capacity across neighborhoods. These indicators were mapped and aggregated to highlight areas with the highest combined vulnerability, guiding the development of targeted adaptation strategies and informing local policy decisions. The approach enabled the county to identify not only physical infrastructure risks but also social factors that could influence recovery and resilience, providing a more holistic basis for planning and resource allocation.

Spatial Analysis

Spatial analysis leverages geographic information systems (GIS) and spatial data layers to visually and quantitatively assess the intersection of hazards (such as floodplains, storm surge zones, or areas of high runoff) with critical assets and populations. By overlaying hazard maps with infrastructure, land use, and demographic data, agencies can produce clear, map-based outputs that highlight which neighborhoods, facilities, or system components are most exposed to specific hazards. This approach directly addresses exposure by identifying where hazards and assets coincide, and often represents sensitivity through the type, function, or criticality of assets located within hazard zones, or through demographic characteristics of affected populations.

While spatial analysis excels at visualizing exposure and, to some extent, sensitivity, adaptive capacity is less frequently analyzed in spatially explicit terms. Some assessments incorporate spatial indicators of social vulnerability—such as poverty rates, vehicle access, or proximity to emergency services—to provide a partial view of adaptive capacity across different areas. One of the key strengths of spatial analysis is its ability to reveal clusters of risk, spatial patterns, and potential cascading effects across interconnected systems, supporting more targeted and effective adaptation planning.

However, the utility of spatial analysis is often constrained by the availability, quality, and resolution of hazard and asset data. Adaptive capacity remains challenging to represent spatially, as relevant data are often limited or not easily mapped. As such, spatial analysis is most powerful when used to support risk screening, prioritization, and communication, and is often complemented by other assessment methods to provide a more comprehensive understanding of vulnerability.

Implementation Guidance

Agencies using spatial analysis for stormwater vulnerability assessment could consider the following options:

- Hazard-asset overlay mapping: GIS assessment of hazard layers (e.g., floodplains, inundation zones) and infrastructure or population data to identify assets or neighborhoods at greatest risk.
- Hotspot and cluster analysis: Spatial statistics that identify clusters of high vulnerability, such as concentrations of critical facilities or socially vulnerable populations within hazard zones.
- Network analysis: Map and analyze the connectivity of stormwater infrastructure to assess how disruptions in one area could cascade through the system.
- Spatial social vulnerability: Mapping: Spatially-explicit social indicators (e.g., Social Vulnerability Index, access to transportation) that highlight areas where adaptive capacity may be limited.
- Scenario mapping: Map how projected changes in climate, land use, or infrastructure could alter exposure and vulnerability patterns over time.

As agencies implement spatial analysis, they should ensure that data sources are up-to-date, accurate, and at an appropriate resolution for decision-making. It is important to document data limitations and methodological choices, and to supplement spatial findings with qualitative or expert input where adaptive capacity or system complexity cannot be fully captured in maps. As the above approaches become more time and resource-intensive, challenges can emerge. For example, conducting network analyses of stormwater conveyance systems may need to contend with gaps in available data on system condition and connectivity. In many jurisdictions, information on the physical and operational status of pipes or channels (e.g., blockages, partial capacity, or disconnections) is sparse relative to documented BMP inventories. As a result, network analyses may need to rely on proxies, assumptions, or iterative validation with field data. Agencies should account for these types of uncertainties when applying or interpreting results.

Vulnerability Assessment Team

Spatial analysis relies on technical proficiency in GIS and spatial data interpretation. Teams typically include GIS specialists, engineers, and planners who can integrate hazard, asset, and demographic datasets. Input from emergency managers and community members can help ensure maps accurately reflect on-the-ground realities and community concerns. While much of the work may be technical, coordination across departments is critical to avoid data silos and ensure results directly inform planning and communication efforts.

Spatial Analysis in Practice

The Washington, D.C. stormwater vulnerability assessment demonstrates the use of spatial analysis by overlaying flood hazard maps with infrastructure and social vulnerability data. The assessment identified neighborhoods where critical facilities and socially vulnerable populations were co-located within high-risk flood zones, enabling the city to prioritize adaptation investments and emergency planning in those areas. This spatially explicit approach also revealed potential cascading risks across the stormwater network, informing both immediate mitigation actions and long-term resilience strategies. The D.C. example highlights how spatial analysis can support targeted, data-driven decision-making, while also illustrating the importance of integrating multiple data sources and methods to address gaps in adaptive capacity assessment.

Statistical Analysis

Statistical analysis uses historical hazard, loss, and damage data to develop models that quantitatively estimate the effects of future hazards on stormwater systems. This approach is data-intensive, requiring robust records of past event frequencies, magnitudes, and associated impacts, as well as the use of climate projections, to support calculations of potential future risks. Exposure is assessed by analyzing where and how often hazards—such as flooding or extreme

precipitation—have occurred in the past and how projections of future precipitation increase or change that exposure, while sensitivity is addressed by quantifying the damages, disruptions, or losses resulting from those events. Statistical analysis is commonly employed in local hazard mitigation planning, especially in communities with standardized hazard mapping (e.g., FEMA Special Flood Hazard Areas) and comprehensive historical records.

While statistical analysis provides strong quantification of exposure and sensitivity, adaptive capacity is typically addressed only indirectly. For example, agencies may note improvements in outcomes attributable to previous adaptation actions, but rarely model alternative adaptive measures or systematically evaluate their effectiveness. The approach's reliance on historical data and technical expertise can be a barrier for some agencies, and its retrospective nature may limit its usefulness for future-oriented planning under climate change unless projections or scenario modeling are incorporated.

Implementation Guidance

Agencies using statistical analysis for stormwater vulnerability assessment could consider the following options:

- **Event frequency analysis:** Analyze historical records to determine how often specific hazards (e.g., flooding, heavy rainfall) have occurred in different locations, comparing these to climate projections of future event frequency.
- **Damage and loss quantification:** Use available data to calculate the financial, physical, and social impacts of past hazard events on infrastructure, housing, and community services.
- **Trend analysis:** Examine changes in hazard frequency, magnitude, or impact over time to identify emerging risks or the effectiveness of past adaptation measures.
- **Scenario modeling:** Incorporate climate projections or land use changes to adjust historical statistics and estimate future vulnerability under different scenarios.
- **Integration with other methods:** Combine statistical findings with spatial analysis or expert judgement to validate results and address gaps in adaptive capacity assessment.

As agencies implement statistical analyses, they should ensure the quality and completeness of historical data, document assumptions and methodologies, and recognize the limitations of retrospective approaches for future planning. Where possible, supplement statistical analysis with scenario modeling or qualitative insights to better account for changing hazard patterns and adaptive capacity. For example, when carrying out event frequency analysis, the selection of the event to be analyzed is critical, as traditional stormwater management design storms typically focus on the 1-, 2-, or 10-year, 24-hour storm. However, precipitation patterns are changing: storms are increasingly rising in frequency, magnitude, and duration, and, in some areas, are now more often characterized by extremely short-term, high-intensity rainfall events. Consequently, event frequency analysis should account not only for traditional design storms but also for these emerging patterns to ensure accurate assessment of future flood risks.

It is also important to note that conducting robust statistical analyses—especially those that incorporate climate projections—can be time-intensive and may require specialized expertise in data management, statistical modeling, and climate science. Agencies should plan for sufficient time and resources to collect, clean, and analyze data, and may need to engage external experts or partner with academic institutions to accurately interpret and apply climate projections in their vulnerability assessments.

Vulnerability Assessment Team

A statistical analysis approach requires staff experienced in data compilation, statistical modeling, and interpretation of hazard and loss information. Agencies may draw on internal analysts or partner with universities or consultants for complex modeling or use of climate projection data. Engineers and planners should participate to ensure the models address practical management questions, while staff familiar with local incident records can help validate datasets. Given the technical demands, this approach often benefits from collaboration between technical experts and decisionmakers to translate results into actionable planning insights.

Statistical Analysis in Practice

The 2016 “Climate Ready Boston” report exemplifies the use of statistical analysis in vulnerability assessment. As part of a broader, decade-long effort, Boston agencies analyzed historical and projected data on stormwater flooding, coastal and riverine flooding, and extreme heat. The report includes financial estimates of losses to housing, critical infrastructure, and economic output, with calculations framed in terms of physical damages, service disruptions, lost productivity, displacement, and other stressors. These analyses are presented at varying spatial resolutions and incorporate both current and future levels of vulnerability, adjusting probabilities and magnitudes of hazards using climate projections and scenario modeling. The Boston example demonstrates how statistical analysis, when complemented by spatial and modeling approaches, can provide a robust foundation for targeted adaptation planning and resource allocation.

Modeling

Modeling involves simulating the physical, operational, or socio-economic response of stormwater systems—and the communities they serve—to a range of hazard scenarios, including those driven by projected climate impacts. This is the most technically advanced approach, commonly employing hydrologic and hydraulic models, system dynamics modeling, or agent-based frameworks. Through these simulations, agencies can estimate potential flooding depths, service disruptions, or network effects under specific storm intensities, enabling highly detailed analysis of system vulnerabilities. This differs from statistical analysis in that it focuses more on the mechanistic processes leading to exposure or other system impacts. Statistical analyses often derive correlations between prior events and impacts. In modeling approaches, exposure is

directly modeled using input hazard scenarios, while sensitivity is measured by projected damage, service loss, or the number of affected populations.

The integration of adaptive capacity into modeling is often limited, as these models require detailed, high-quality data on existing and planned mitigation measures, system redundancies, response times, institutional resources, and population behaviors—data that may not always be available or easily represented in model frameworks. Despite these challenges, advanced modeling is essential for agencies managing complex urban stormwater systems and multi-hazard risks, particularly when supporting large-scale capital investments, regulatory compliance, or long-term adaptation planning.

Implementation Guidance

Agencies using modeling for stormwater vulnerability assessment could consider the following options:

- Hydrologic and hydraulic modeling: Modeling of stormwater flows, flooding depths, and drainage system performance under various rainfall scenarios to identify infrastructure vulnerabilities and inform design improvements.
- Scenario-based simulations: Model the impacts of different hazard scenarios (e.g., future extreme precipitation, sea level rise) on system operations and infrastructure impacts, supporting emergency response and adaptation planning.
- System dynamics or agent-based modeling: Agent-based or system dynamics models can simulate how changes in infrastructure, population, or policy might affect system performance and vulnerability over time, including feedbacks and cascading effects.
- Integration of mitigation measures: Models can be used to examine how existing or planned adaptation strategies (e.g., green infrastructure, pump upgrades) are effective or not in reducing vulnerability.
- Stakeholder engagement in model development: Modeling efforts can involve technical staff, planners, and community representatives to define model parameters, validate outputs, and interpret results to ensure relevance and buy-in.

As agencies implement modeling approaches, they should plan for significant time and resources, as model development, calibration, and scenario analysis can be complex and labor-intensive. Specialized expertise in hydrology, engineering, and climate science is often required, and agencies may need to partner with consultants, academic institutions, or regional technical centers. It is also important to document model assumptions, data sources, and limitations, and to communicate results in accessible formats for decision-makers and stakeholders.

Vulnerability Assessment Team

Modeling approaches demand the highest level of technical expertise. Teams typically include water resources engineers, GIS and data specialists, and planners familiar with system operations and adaptation goals. Because modeling requires detailed assumptions about infrastructure and scenarios, collaboration with consultants, regional technical centers, or academic institutions is common. Engagement with operations staff helps ensure models reflect

real system behavior, while planners and decisionmakers play a key role in interpreting outputs for investment and policy decisions.

Modeling in Practice

The Boston Water and Sewer Commission’s adaptation planning provides a clear example of modeling in action. The Commission used advanced hydrologic and hydraulic models to simulate future stormwater outflows under a range of climate scenarios, including increased rainfall intensity and sea level rise. These simulations identified critical infrastructure at risk of flooding and service disruption, informing both emergency response strategies and long-term capital investment decisions. The modeling outputs were integrated with spatial and statistical analyses to provide actionable guidance for infrastructure upgrades, regulatory compliance, and stakeholder engagement, demonstrating the value of modeling for comprehensive vulnerability assessment and adaptation planning.

A Step-by-Step Framework for Conducting Vulnerability Assessments

Table 5 provides a high-level overview of key steps an agency could take for the whole of the vulnerability assessment. While *Step 1. Determine Assessment Purpose and Scope* and *Step 2. Select and Implement Assessment Approach* are both covered in detail in Part 2, Table 5 is designed to build on those sections by summarizing them and providing direction for what comes next—helping agencies move from defining their purpose and selecting an approach to implementing, evaluating and communicating findings.

Table 5. Vulnerability Assessment Process: Step-by-Step Table

Step	What to Do	Why This Matters	Key Questions to Ask
1. Determine Assessment Purpose and Define Scope	<ul style="list-style-type: none"> Clearly state objectives (e.g., compliance, planning, investment) Identify hazards to address Define boundaries: geography, infrastructure, populations Consider decision context and audiences 	A well-defined goal and scope keep your assessment focused and ensure useful results.	<ul style="list-style-type: none"> What decisions will this assessment inform? Who are the key audiences? What hazards and system elements are most relevant?
2. Select and Implement Assessment Approach	<ul style="list-style-type: none"> Review goals, resources, and timeline Using the decision guidance in this document, select approach (e.g., expert judgement, spatial analysis, modeling) Align approach with output needed for regulatory and local priorities Match approach to technical/data capacity 	The right approach ensures your assessment is feasible and fit for purpose.	<ul style="list-style-type: none"> What methods are realistic given our resources? Do we need detailed modeling, or will a simpler approach suffice? Are there regulatory requirements to meet?
3. Engage Stakeholders	<ul style="list-style-type: none"> Identify key stakeholders (agencies, experts, community) Involve them early and often (workshops, interviews, surveys) Use input to validate data and findings 	Stakeholder input grounds your assessment in local knowledge and builds support	<ul style="list-style-type: none"> Who needs to be involved? How will we gather and use their input? How can we ensure diverse perspectives are included?
4. Collect and Organize Data	<ul style="list-style-type: none"> Gather relevant data (infrastructure, hazards, population) Review prior reports and plans Organize data for analysis Use proxies or expert judgement to fill gaps 	Good data is the foundation of a credible assessment	<ul style="list-style-type: none"> What data do we have? Where are the gaps? How will we address missing information?
5. Assess Vulnerability	<ul style="list-style-type: none"> Exposure: Characterize where and how often elements are exposed Sensitivity: Evaluate how severely elements would be affected Adaptive Capacity: Assess ability to reduce/recover from impacts Integrate findings to identify most vulnerable elements 	This step identifies what is most at risk and why	<ul style="list-style-type: none"> Which assets, populations, or functions are most exposed? What makes them sensitive? How well can they adapt or recover?
6. Implement and Communicate Findings	<ul style="list-style-type: none"> Develop clear, actionable recommendations Prioritize measures (upgrades, risk reduction, policy changes) Prepare accessible communication products (maps, dashboards, reports) Share results and document process/lessons learned 	Turning results into action is the ultimate goal	<ul style="list-style-type: none"> What actions should be taken? How will we communicate findings? How will we track progress and update the assessment?

Drawing on established best practices and lessons from the literature, the following additional recommendations are intended to enhance the rigor, relevance, and utility of a vulnerability assessment:

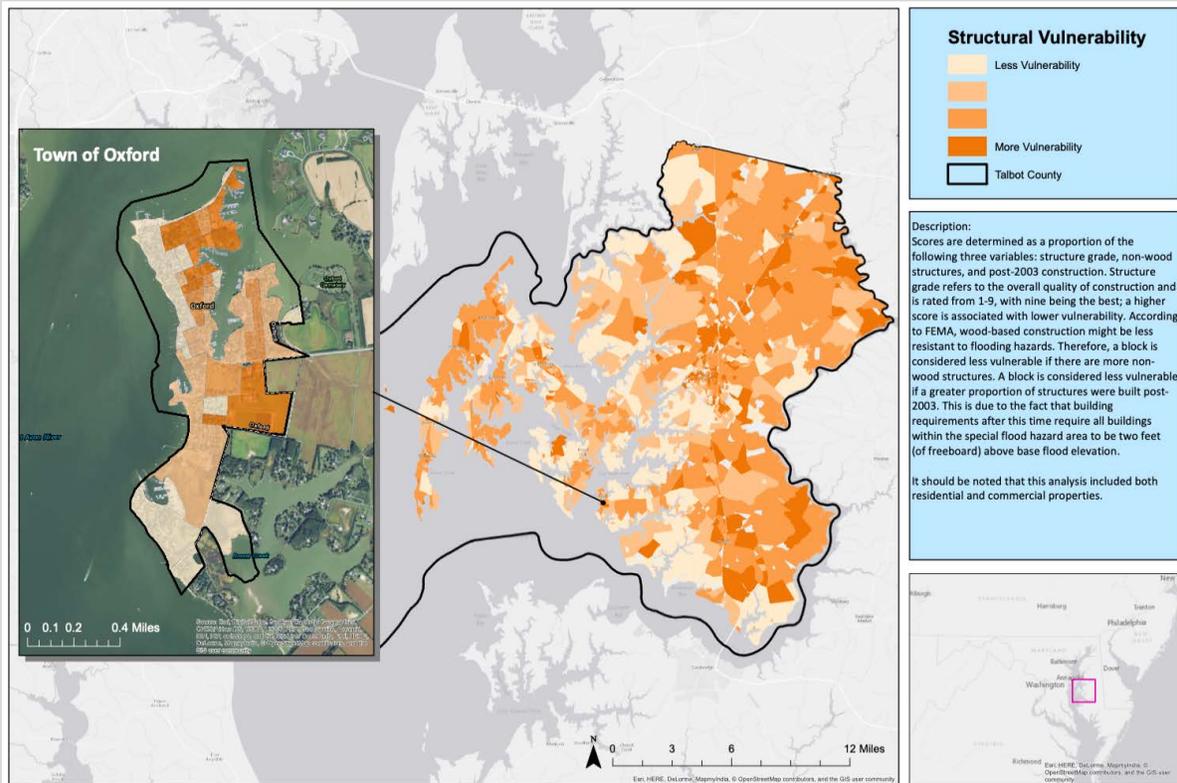
- Engage stakeholders throughout the process, not just at the beginning or end.
- Be transparent about data limitations and how you addressed them.
- Align your assessment with other local and regional planning efforts for maximum impact.
- Use Appendix C for a list of data sources to get started.
- See Box 7 for a real-world example from Oxford and Talbot County, Maryland.
- The case studies presented in Part 4 of this guide provide an overview of how other agencies followed the steps outlined above.

Box 7. Vulnerability Assessment for Town of Oxford and Talbot County, Maryland

The Town of Oxford and Talbot County, Maryland undertook a NOAA-led vulnerability assessment that integrated block-level population data, asset-level structural data, and resource inventories to develop science-based indicators of vulnerability. This assessment used proxy indicators for specific hazards such as stormwater flooding and loss of natural resources where models were lacking and combined structural (see figure below) and social vulnerability measures for to help prioritize climate adaptation efforts and investments.

The goal of the vulnerability assessment was to support climate adaptation planning in coastal communities. Key steps included:

1. Collecting data and integrating block-level population data, asset-level structural data, and natural resource inventories from local, state, and national sources.
2. Mapping stormwater exposure based on elevation, land cover, and soil type to identify areas prone to hazard.
3. Assessing structural vulnerability for residential and commercial buildings using factors such as building material, age (relative to elevation requirements), and parcel-level building grades.
4. Calculating social vulnerability scores at the census block level via a multi-variable index.
5. Assigning adaptation priority scores using a combination of risk analysis (e.g., surge and stormwater impact) and the previously derived social and structural vulnerability scores.
6. Conducting a qualitative discussion of existing adaptive capacity and opportunities for enhancement.



Part 4: Vulnerability Assessment Case Studies

The case studies in the following three sections illustrate how various agencies have conducted vulnerability assessments tailored to their specific context, objectives, and resource constraints. By examining the implementation process, the intended applications, and the

selection of methodological approaches in each example, these cases offer valuable insights and practical guidance for stormwater agencies planning their own assessments. Each example demonstrates a unique combination of analytical techniques and stakeholder engagement practices, highlighting both the opportunities and challenges encountered in operationalizing vulnerability assessment for stormwater management and climate adaptation. Together, these real-world cases serve as informative references for agencies seeking to design, conduct, and apply vulnerability assessments to meet their own goals.

Additional vulnerability assessments are detailed in Appendix B.

Case Study 1 – Goshen, Indiana

Step 1: Set Goals and Scope

Goshen began by defining the main objective of their vulnerability assessment: to understand local risks related to flood hazards and extreme heat—primary climate threats recorded in regional and local trend data. The assessment aimed to support both regulatory processes and guide the city’s ongoing efforts in resilience, public safety, and stormwater infrastructure planning. The geographic boundary for analysis was set as the City of Goshen. System boundaries included all major stormwater management infrastructure, particularly in the urban core, as well as the community’s residential population, critical facilities, and areas of known social vulnerability. The assessment explicitly aimed to identify which neighborhoods and systems were most exposed or sensitive, ensuring results would be relevant to stakeholders and align with the city’s broader climate and capital improvement goals.

The Goshen vulnerability assessment was conducted through the FloodWise Communities Program² in collaboration with the City of Goshen, with contributions from the Mayor, Stormwater Department, Environmental Resilience Department, Public Works, Floodplain Administration, Community Relations, and other City departments (City of Goshen, 2025).

Step 2: Determine Approach

Given available staff, moderate data resources, and a mix of qualitative and quantitative objectives, Goshen selected a blended approach. This approach integrated indicator-based quantitative analysis (e.g., mapping of impervious surfaces, floodplains, tree canopy), limited spatial analysis (overlying physical and demographic risk), and qualitative characterization of vulnerability (through input from local knowledge and synthesis of secondary data).

Specifically, the assessment included:

- *Indicator-Based Quantitative Analysis:* Goshen mapped and analyzed indicators such as percent impervious surface, floodplain extent, and tree canopy coverage. Using available GIS and land cover data, these indicators helped to consistently evaluate and score the

² More information on the FloodWise Communities Program can be found at: <https://glisa.umich.edu/engagement/floodwise-communities/>

vulnerability of different neighborhoods and stormwater system areas. This provided a semi-quantitative means to compare physical vulnerability across the city.

- *Limited Spatial Analysis:* The team conducted spatial overlays to examine where physical vulnerabilities (such as high impervious surface and floodplain overlap) were co-located with demographic and socioeconomic risk factors. They used spatial mapping techniques to visualize which neighborhoods and infrastructure were most exposed to hazards, supporting the identification of at-risk assets and communities.
- *Expert Judgement:* Local knowledge was gathered through city staff, field experience, and input from officials familiar with recent flood events and on-the-ground conditions. This qualitative input shaped an understanding of where vulnerabilities existed that might not be captured by quantitative data—such as particular streets, parks, or neighborhoods known to repeatedly flood.

By combining these elements—indicator-based scoring, spatial overlays, and expert judgement from both staff and the community—Goshen achieved a layered vulnerability assessment tailored to both the city’s hazard mitigation planning requirements and its climate resilience objectives. This approach allowed for Goshen to prioritize solutions even with moderate staff and data resources.

Step 3: Engage Stakeholders

Throughout the assessment process, Goshen actively engaged multiple stakeholders—including city engineers, public works staff, planners, local emergency management, and regional resilience partners. Stakeholder input was gathered to supplement and contextualize quantitative findings, especially where census- or index-based data proved too coarse to capture neighborhood-level vulnerability. This engagement helped confirm priority assets and neighborhoods, interpret technical findings, and build support among decision makers and the public.

Step 4: Collect Data

The team gathered a range of spatial and non-spatial datasets:

- Local infrastructure inventories: locations and conditions of stormwater pipes, outfalls, and retention basins.
- GIS layers: FEMA floodplain maps, the USGS National Land Cover Database highlighting impervious and vegetated surfaces, and Landsat data for urban heat island mapping.
- Demographic and socioeconomic data: U.S. Census information, CDC Social Vulnerability Index, and Headwaters Economics’ Neighborhoods at Risk tool.
- Historic and projected climate data: documented local climate trends and state-level climate projections.
- Prior studies and planning documents: city and county hazard mitigation plans, engineering reports, and flood resilience strategies.

Step 5: Assess Vulnerability

- *Exposure:* Goshen primarily used spatial analysis by mapping intersections of stormwater infrastructure and population centers with flood-risk zones (using FEMA maps), urban heat islands (using remote sensing and Landsat thermal data), and impervious surface areas (from land cover datasets). Indicator-based analysis was also employed through the use of metrics such as percent impervious surface and tree canopy coverage, as well as referencing local climate trends and projections. These quantitative indicators allowed the team to compare exposure across different city areas.
- *Sensitivity:* The assessment relied on a mix of indicators (e.g., infrastructure age, manufactured housing density, socioeconomic factors like poverty and car access) and expert judgement informed by local staff's on-the-ground knowledge and experiences from recent flood events. There was qualitative interpretation layered onto this quantitative and mapped information, especially to clarify or validate areas that were particularly prone to damage or difficult to capture with quantitative data alone.
- *Adaptive Capacity:* The team used expert judgement and qualitative analysis to evaluate factors such as redundancy in stormwater networks, the availability of emergency services, and community/institutional response capacity. These qualitative assessments were necessary due to limited quantitative data about organizational and social resources.
- *Integrate Findings:* The integration step involved both spatial analysis and scorecard-like synthesis, overlaying exposure, sensitivity, and adaptive capacity data to identify the most vulnerable catchments, facilities, and neighborhoods. Quantitative indicators were mapped and synthesized, while expert judgement and qualitative review helped to interpret results and prioritize concerns.

Step 6: Implement and Communicate Findings

Results were distilled into accessible products: neighborhood-level maps, summary documents for public communication, and technical memos for decisionmakers. Findings were used to inform ongoing planning (e.g., aligning with the Flood Resilience Plan), support grant applications, and enhance coordination with regional adaptation efforts (City of Goshen, 2025).

Case Study 2 – Baltimore, Maryland

Step 1: Set Goals and Scope

Baltimore's vulnerability assessment began by explicitly defining the primary objective: to identify and prioritize vulnerabilities to flooding and climate-related hazards across the city, with a focus on both stormwater infrastructure and the populations most at risk. The assessment established boundaries including a citywide geographic extent, covering a range of infrastructure types (e.g., stormwater networks, combined sewer systems, critical facilities) and relevant populations (e.g., communities with socioeconomic and historical vulnerability). The scope was set to ensure results were relevant to ongoing planning efforts and regulatory requirements, and to align with the city's climate resilience, sustainability, and equity objectives.

The Baltimore Disaster Preparedness and Planning Project (DP3) (2023) was led by a core planning team from the Office of Sustainability, Office of Emergency Management, Department

of Planning, and Department of Public Works, with support from a broad advisory committee of local, state, and federal stakeholders, community organizations, and a social equity subcommittee (Baltimore City, 2023).

Step 2: Determine Approach

Baltimore selected a multi-method approach that integrated both qualitative and quantitative elements, reflecting available resources, regulatory expectations, and the complexity of hazards facing the city. This included the use of expert judgement and structured stakeholder engagement to identify and validate priority hazards and vulnerabilities, the development of qualitative scorecards for initial screening, and the application of spatial analysis (e.g., mapping flood-prone areas and overlaying infrastructure and population data). Proxy indicators (such as socio-demographic metrics and infrastructure age) were used where direct data or models were lacking. The city leveraged regional/state partnerships and prior studies to maximize data coverage and interpretation given technical and resource constraints.

Baltimore's approach exemplifies a layered assessment: regulatory modeling (using Hazus/FEMA methods for compliance and grant alignment), robust GIS-based exposure and overlay analyses, integration of social vulnerability data, and structured qualitative/stakeholder validation. Specifically, they used nearly all approaches:

- *Expert Judgement*: The assessment leveraged structured input from subject matter experts and stakeholders at multiple points, including the identification and validation of priority hazards, reviewing results, and interpreting uncertainties or data limitations. This included professional judgement to refine probability estimates, hazard ranking, and scenario selections, particularly for hazards and impacts where quantitative data or models were less robust.
- *Scorecards*: For initial hazard screening and prioritization, and where detailed modeling was not available, Baltimore used qualitative scorecards. These incorporated weighted factors such as probability of occurrence, impact to people/buildings/economy, adaptive capacity, and projected climate change, producing standardized relative risk scores for each hazard.
- *Indicators*: Indicator-based screening was central, with the use of proxy variables such as infrastructure age, maintenance status, social vulnerability indices (e.g., CDC SVI), and land use categories wherever direct modeling or fine-scale data were lacking. These indicators informed both the citywide hazard risk ranking and localized exposure/sensitivity analyses.
- *Spatial Analysis*: GIS asset mapping formed the foundation for exposure assessment. Hazard maps (for floods, hurricanes, heat, hazardous materials, etc.) were overlaid with spatial inventories of buildings, critical infrastructure, and population data to determine which assets and neighborhoods were at risk. The team overlaid social vulnerability indices with hazard maps to identify areas where at-risk communities matched high-exposure zones, supporting targeted analysis of equity impacts. Overall, the assessment produced extensive maps visualizing exposure, risk, and social vulnerability distributions citywide and by neighborhood.

- *Statistical Analysis*: The assessment incorporated quantitative estimation of impact using inventory counts, loss estimation calculations, exposure statistics, demographic analyses, and spatial queries (e.g., counting or summing assets, populations, or property values within hazard zones).
- *Modeling*: The city conducted detailed risk and loss modeling using FEMA’s Hazus software at Level 2, which uses customized, city-specific inventories for more accurate loss estimation for hazards such as flood, hurricane wind, and earthquake. Level 3 analyses, requiring detailed engineering or geotechnical information, were performed for select high-priority assets or locations with sufficient data.

Step 3: Engage Stakeholders

Throughout the assessment process, Baltimore actively engaged city agencies (e.g., public works, emergency management, planning), community organizations, technical experts, and regional partners. Engagement included convening workshops, soliciting local knowledge, and reviewing findings with stakeholders for validation and prioritization. This collaborative approach ensured that the assessment reflected local experience, built buy-in across agencies, allowed for the integration of diverse perspectives, and enhanced credibility for both technical and community audiences.

Step 4: Collect Data

Baltimore gathered a broad set of spatial and non-spatial data, including:

- Maps of stormwater infrastructure, critical facilities, and combined sewer systems
- FEMA flood maps and records of historical flooding and infrastructure performance
- Socioeconomic and demographic data at the neighborhood and block level, including social vulnerability indices
- Land use and land cover data to support spatial overlays of risk factors
- Past local and regional planning documents and prior assessments to inform data synthesis and provide historical context
- Where data gaps existed, the city relied on proxy indicators (such as age of infrastructure or presence of vulnerable populations) and qualitative local knowledge.

Step 5: Assess Vulnerability

- *Exposure*: Baltimore’s analysis of exposure relied heavily on spatial analysis, employing GIS to map flood-prone areas and other projected hazard zones, and overlaying these with locations of infrastructure assets and population data. This process made use of indicators such as asset location, population density, and the presence of critical facilities. Where applicable—particularly for hazards such as floods and earthquakes—modeling was performed using FEMA’s HAZUS software to simulate and estimate the geographic extent and severity of exposure. Expert judgement and historic event review were also incorporated to refine hazard zone delineation and account for local conditions not fully captured by quantitative data.
- *Sensitivity*: Sensitivity was evaluated through the use of indicators (e.g., infrastructure age, building condition, maintenance status), drawing from available asset inventories

and social vulnerability indices. Scorecards were developed to standardize assessment and comparison of how susceptible assets, facilities, or neighborhoods might be to damage or disruption. Expert judgement supported the interpretation of these indicators, especially in rating assets or neighborhoods where data were limited, and in identifying critical facilities or populations likely to be severely impacted.

- *Adaptive Capacity*: The analysis of adaptive capacity was largely qualitative, informed by expert judgement about Baltimore’s current administrative, technical, regulatory, and financial capabilities. This included assessing redundancy in infrastructure, maintenance practices, planning resources, and social or institutional support systems. Key capacities were rated as strong or weak based on structured reviews of core capabilities, providing a comparative basis for adaptive capacity across different neighborhoods or system elements.
- *Integrate Findings*: Baltimore combined these component analyses using scorecards and spatial overlays. Risk scoring matrices brought together exposure, sensitivity, and adaptive capacity to rank neighborhoods, facilities, or systems. Expert judgement played a role in validating and interpreting the final vulnerability rankings, particularly when weighing uncertainties or adjusting for unique local circumstances. The result was a set of citywide and neighborhood-level risk profiles that guided strategic planning and resource prioritization.

Step 6: Implement and Communicate Findings

Baltimore utilized assessment findings to develop recommendations for infrastructure upgrades, risk reduction measures, and adaptation strategies. Outputs included prioritized lists and maps of at-risk neighborhoods and assets, summary documents, and scorecard results to communicate to decision-makers and the public. The city used visuals to promote understanding and planning across agencies and engaged stakeholders in reviewing and refining recommended actions, supporting ongoing implementation and resilience-building efforts (Baltimore City, 2023).

Case Study 3 – Washington, D.C.

Step 1: Set Goals and Scope

Washington, D.C.’s vulnerability assessment began by clarifying its primary objective: to identify which neighborhoods, infrastructure, and populations were most at risk from a range of climate and stormwater-related hazards. Hazards addressed included flooding, extreme heat, and related infrastructure strains. The assessment covered the entire District, including all major stormwater systems, critical facilities, residential areas, and especially neighborhoods historically impacted by flooding or with vulnerable populations. The goal was to support both compliance objectives and long-term resilience planning by ensuring the scope aligned with regulatory expectations and broader city goals.

The 2016 Washington, D.C. vulnerability and risk assessment was prepared by consultants Perkins+Will and Kleinfelder for the D.C. Department of Energy and Environment (Department of Energy and Environment, 2016).

Step 2: Determine Approach

D.C. chose a mixed-methods, intermediate-level assessment strategy. This included:

- The use of indicator-based scoring to evaluate vulnerability at the block or neighborhood level.
- Overlaying spatial data on hazards (e.g., floodplains, heat exposure) with physical and social asset data.
- Use of scorecards and proxy indicators—such as percent impervious area, infrastructure age, and social vulnerability metrics—to compensate for data or modeling gaps.
- Selective spatial modeling to estimate exposure, complemented by qualitative review to integrate local knowledge and regulatory requirements.

Step 3: Engage Stakeholders

D.C. involved a broad group of stakeholders: local agency staff, technical experts, decision makers, and community representatives. Methods included workshops, structured panels, and open meetings, which helped ground the assessment in on-the-ground realities, shape priorities, and validate initial outputs. Stakeholder engagement continued throughout the process to refine assessment tools (such as vulnerability scorecards and indicator frameworks) and build support for subsequent actions.

Step 4: Collect Data

The assessment team gathered a comprehensive dataset including:

- GIS maps of existing stormwater and drainage infrastructure, and locations of critical facilities.
- FEMA flood maps, historic hazard occurrence data, climate projections, and surface heat mapping.
- Socioeconomic and demographic data at the block or census tract level.
- Land use, land cover, and impervious surface data to inform both risk and adaptation priority scoring.
- Prior planning documents, engineering reports, and regulatory filings were reviewed to ensure all relevant context and history was integrated.

Step 5: Assess Vulnerability

- *Exposure:* The team used spatial analysis to map flood-prone and heat-vulnerable areas, overlaying these hazard zones with infrastructure and population data to quantify where systems and populations were most exposed. Indicators such as the presence of infrastructure in FEMA flood zones and areas of known heat vulnerability were central. Where available, statistical analysis of stormwater system performance and historical event data further informed the exposure assessment.

- *Sensitivity*: Sensitivity was assessed using indicators (e.g., age and condition of infrastructure, population density, CDC SVI or similar indices) to rate the susceptibility of assets and neighborhoods to hazard impacts. Scorecards and expert judgement supplemented this process, particularly in evaluating locations with repeated disruption or data gaps.
- *Adaptive Capacity*: Both quantitative and qualitative approaches were used, relying on indicators (such as redundancies in critical systems and emergency resources) and expert judgement about the effectiveness of existing management practices and community capacity. This helped characterize the ability of systems and communities to respond to and recover from stormwater-related hazards.
- *Integrate Findings*: The assessment combined these results using scorecards and spatial analysis to generate multi-dimensional vulnerability scores. This integration supported prioritization at the block or neighborhood level, identifying which system elements and populations were most in need of targeted adaptation or mitigation actions.

Step 6: Implement and Communicate Findings

D.C. used the vulnerability assessment findings to prioritize infrastructure upgrades and risk-reduction investments and improve coordination for regulatory compliance. The city prepared a suite of communication products, including maps highlighting hotspots, scorecard summary tables, and public-facing summary documents. These products were used to engage stakeholders, inform decision makers, and support the integration of vulnerability findings into citywide resilience and adaptation planning initiatives.

Appendix A. Background and Methods

This appendix presents our initial findings from a comprehensive literature review and a series of regional stakeholder interviews, undertaken to inform the development of this guidebook for stormwater agencies. The purpose of this effort was to identify and synthesize leading approaches, practical challenges, and real-world applications of vulnerability assessments relevant to stormwater infrastructure and climate adaptation.

We begin by briefly describing our review process and interview methodology, followed by a synthesis of findings organized around several central questions:

- What constitutes a vulnerability assessment in the context of stormwater management?
- How are stormwater and related agencies currently designing and implementing vulnerability assessments?
- What are the primary factors shaping agency choices regarding assessment approach, scope, and methodology?
- What key barriers and challenges do agencies face in conducting meaningful vulnerability assessments?

These topics are supplemented by detailed insights drawn from seven case studies of vulnerability assessments conducted by diverse agencies, which are included in Appendix B. The collective findings in this section serve as both background and foundational evidence for the guidance and recommendations presented throughout this guidebook.

Approach

The literature review employed a semi-structured approach to collect and examine vulnerability assessments, including hazard mitigation plans and related hazard or risk assessments relevant to stormwater management, flood hazards, and climate adaptation. Priority was given to reports published within the Chesapeake Bay region, as well as those from other areas experiencing stormwater flooding, with a focus on coastal and urban regions. Additional emphasis was placed on reports produced by or for agencies familiar to the authors or recommended by interviewed stakeholders. The review also included pertinent documents from stormwater agencies beyond formal vulnerability assessments and a selection of academic literature addressing the theory and practice of vulnerability assessments.

The collected materials were synthesized with several objectives in mind. First, we sought to characterize the breadth of vulnerability assessment approaches, with attention to the distinction between foundational and more advanced methodologies. We also examined the tools, data sources, and frameworks used across different assessments. Particular attention was given to approaches used within the Chesapeake Bay region, especially those addressing stormwater

flooding. Finally, we analyzed how contextual factors—such as agency goals, institutional capacity, and regional risk profiles—influence the structure and content of vulnerability assessments.

We conducted 12 semi-structured interviews with stakeholders from a range of organizations involved in stormwater management and climate adaptation. Interviewees represented local governments (MS4 and CSO permit holders), regional planning commissions, federal agencies, a state transportation department, and a quasi-governmental resilience authority. This mix of institutional types and geographic contexts provided a broad perspective on the challenges, tools, and approaches used in vulnerability assessments.

Interviews were guided by a set of open-ended questions focused on how organizations conceptualize and assess vulnerability, the role of vulnerability assessments in their work, and the barriers and opportunities associated with integrating climate change into stormwater planning. Interviewees were asked about the types of vulnerabilities most relevant to each organization, the extent to which vulnerability assessments had been implemented, and, where applicable, the tools and approaches used, as well as their perceived strengths and limitations. We also asked stakeholders about how they would like to use vulnerability assessments, the types of support or guidance that would be most useful, and the organizational constraints—such as time, resources, or institutional capacity—that may limit their capacity to carry out vulnerability assessments.

What is a vulnerability assessment?

Based on our review of vulnerability assessments and relevant academic literature, the most inclusive and fundamental description of vulnerability assessments is the assessment of a system's susceptibility to hazards. In practice, the vulnerability of a system (e.g., a region or a utility that spans a region) is assessed through different lenses, which can each constitute their own assessment or be layered to characterize overall vulnerability. For example, the vulnerability assessment can examine selected system elements such as assets (e.g., general building stock or natural resources), functions (e.g., reliability of stormwater outfalls, transportation, or electricity), or populations (particularly sensitive populations) to individual hazards.

Beyond these frameworks, research on vulnerability assessments presents varying definitions of vulnerability (Füssel & Klein, 2006; Moret, 2014; Nasiri et al., 2016; Rehman et al., 2019; Teodoro & Naim, 2020; Estoque et al., 2022). These definitions emphasize different system elements and functions (e.g., social, economic, environmental, or physical) and otherwise vary in scope, though all are ultimately captured in our broad definition. What remains largely consistent across the collected literature is the characterization of hazards, reflecting our definition of exposure through considerations such as probability, history, extent, and intensity of hazards, and the estimation of impacts on system elements, reflecting our definition of sensitivity through considerations such as loss, damage, social impacts, and disruptions. Some vulnerability

assessments describe considerations aligned with our definition of adaptive capacity, though such considerations remain uncommon and limited.

An influential framework for vulnerability in the context of climate change comes from the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (AR3) report, which defines vulnerability as “the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity” (McCarthy et al., 2001). Simplified, this framework considers vulnerability as a function of the “exposure”, “sensitivity”, and “adaptive capacity” to climate change-related hazards of elements that comprise a system of interest.

This original framework remains prevalent in literature and in practice, the IPCC framework has changed as of the AR5 and AR6 reports (IPCC, 2014; Estoque et al., 2022), which define risk as a function of vulnerability, exposure, and hazard. In this new framework, the prior definition of exposure is captured by exposure (“whether”) and hazard (“how” and “how frequently”) and the prior definitions of sensitivity and adaptive capacity are absorbed into vulnerability. Though the emphasized lens of these frameworks differs, they ultimately capture the same breadth of information. Therefore, though the specific definitions of these terms vary, we adopt the following generic definitions, based upon the AR3 report framework and adapted within the broader context of research on vulnerability assessments:

- Exposure: Whether, how, and how frequently system elements are potentially exposed to hazards
- Sensitivity: The potential impacts of hazards to system elements
- Adaptive Capacity: The capacity to reduce the exposure or sensitivity of system elements to hazards

How are stormwater and other agencies approaching vulnerability assessments?

The literature describes how the scope of vulnerability assessments can vary in terms of emphasized systems (and system elements), emphasized hazards, measures of vulnerability, consideration of climate change, utilized models and data, and application. To understand how these concepts are applied in practice, we reviewed 35 different vulnerability assessments, including deeper case studies for seven vulnerability assessments.

From our review, we derived the following high-level insights:

- Structural vulnerability and functional importance of system elements offer distinct insights; the most comprehensive assessments incorporate both dimensions to understand exposure, sensitivity, and adaptive capacity.
- Adaptive capacity is generally addressed qualitatively and typically limited to select system elements, often due to data or methodological constraints.

- Assessments that include a broad set of climate-related hazards—especially those lacking well-developed spatial models—tend to treat hazards in silos, making it difficult to synthesize findings across threats.
- Technical limitations and data gaps are a near-universal challenge, even in well-resourced assessments, often necessitating trade-offs in scope, resolution, or integration.
- Despite growing interest in assessing the structural damage or performance loss to BMP infrastructure from climate change, there was a notable absence of discussion or assessment of BMP vulnerability in the reviewed materials; this represents a significant gap in current practice.

In the following two sub-sections, we highlight more specific findings from seven vulnerability assessments that reflect a representative range of vulnerability assessment approaches in practice. Below, we divide these assessments into two categories based on the type of planning they informed – Hazard Mitigation Plans and climate adaptation plans, or similar planning efforts. A fuller characterization of each assessment is included in Appendix B.

Hazard Mitigation Plans

Local hazard mitigation plans (HMPs) generally all include some form of vulnerability assessment as a prerequisite for grant and program eligibility (e.g., National Flood Insurance Policy).³ To do so, localities should be equipped with the tools, data, and capacity to achieve basic compliance, which includes standardized analyses and public participation. For most hazard-specific assessments comprising these vulnerability assessments (officially called “risk assessments”), basic compliance is partially achieved through a reproducible process that involves geospatial layering of maps of probabilistic hazard extent (often standardized, as in Special Flood Hazard Area (SFHA) maps of coastal, riverine, and inland floodplains) atop data on properties (including valuations), critical facilities, populations, and historical incidents, yielding tabular data relevant to exposure and sensitivity. These results are accompanied by qualitative summaries. Vulnerability assessments lead to the development, review, and approval of a detailed mitigation strategy with action items delegated to relevant agencies and stakeholders. Noting that new local HMP guidance enacted in 2022 mandates limited analyses of climate change and other long-term considerations (although the majority of reviewed HMPs being published during under prior guidance sunset in 2023), this review has not revealed standardized practices for achieving this new level of compliance (FEMA, 2022).

The 2016 HMP for Elkhart County, IN (Elkhart County, 2016) is an example of an HMP that achieves basic compliance under prior local HMP guidance. Though this effort was scoped precisely in response to mandates, the city of Goshen, IN (one of six participants in the HMP effort) complemented this effort with a vulnerability assessment that emphasizes climate adaptation in the context of stormwater management (Goshen, 2018). This assessment was

³ FEMA removed the requirement to consider climate change in HMPs in April 2025.

conducted as part of the FloodWise Communities (FWC) effort, which has yielded a reusable framework for climate-informed vulnerability assessments. By relying on publicly accessible high-level climate projections, a structured stakeholder engagement process, qualitative descriptions of potential impacts on broad system elements, and a reusable report template, the FWC framework offers a streamlined approach to climate-informed vulnerability assessments for small and mid-sized communities in which stormwater flooding is a major concern. Furthermore, the emphasis on a small set of broad system elements (e.g., a city's stormwater system as a whole; as opposed to a comprehensive set of granular elements such as individual buildings or stormwater drains) facilitates detailed, qualitative discussions of adaptive capacity.

The 2022 Hazard Mitigation Plan (HMP) developed by the Hampton Roads Planning District Commission (HRPDC), encompassing 19 jurisdictions, demonstrates a comprehensive approach that surpasses standard local mandates. This plan benefits from a \$150,000 state grant, builds upon previous initiatives facilitating advanced analyses like HAZUS Level 2, and includes qualitative assessments of climate change impacts on hazards. The collaborative effort leverages shared resources to maintain long-term stakeholder engagement and incorporates technical expertise through consultants (Hampton Roads Planning District Commission, 2022).

Virginia Beach, a participant in the HRPDC HMP, has aligned its efforts through the 2020 Sea Level Wise Adaptation Strategy. This strategy, informed by engineering analyses initiated in 2014, provides a detailed vulnerability assessment addressing flooding and stormwater runoff in the context of sea level rise scenarios (City of Virginia Beach, 2020).

Similarly, Baltimore's HMP is notably ambitious, serving concurrently as the city's official climate adaptation plan. The Disaster Preparedness and Planning Project (DP3) integrates hazard mitigation with climate adaptation, reflecting a policy-driven approach (Baltimore Office of Sustainability, 2023).

The diversity of stakeholders leading HMP efforts appears to influence the scope and depth of the plans. In the HRPDC initiative, leadership primarily comprises emergency management professionals. Conversely, Baltimore's core team includes representatives from emergency management, planning, public works, and sustainability sectors, fostering a multifaceted perspective (Baltimore Office of Sustainability, 2023). This trend is also evident in multi-jurisdictional HMPs from Lehigh Valley, PA, and the Northern Virginia Region, which involve a broad array of stakeholders (Engage Fairfax, 2022). In contrast, the Boston HMP exhibits a more centralized approach with less functional diversity among its leadership.

Climate Adaptation or Related Plans

The review also included vulnerability assessments that are part of climate adaptation planning efforts. Such efforts generally attempt to provide an integrated assessments of several hazards in the context of climate change, are built on years of knowledge and technical capacity development, spatially integrate the outputs from models of climate impacts, and provide a

foundation for subsequent assessment and planning efforts tailored to more specific adaptation functions.

An assessment for the Town of Oxford and Talbot County, MD (a NOAA-led effort showcasing cutting-edge tools and datasets as of 2016) is an example of a highly technical effort in this category. Notably, this effort entailed extensive and innovative collection and application of data block-level population data, asset-level structural data, and natural resource data from local, state, and national sources towards the construction of science-based indicators of vulnerability. This included a selection of indicators that serve as proxies for hazard-specific vulnerabilities beyond modeling feasibilities (e.g., stormwater flooding risks and the loss of natural resources) and a reconstruction of common social vulnerability indicators necessitated by limitations in census data (which omitted certain data for census blocks with smaller populations). Structural and social vulnerability scores aggregated at the block-level were concisely applied to scores that rank block by adaptation priorities and a qualitative discussion of adaptive capacity (Messick et al., 2016).

Another useful example is the 2016 vulnerability assessment from Washington, D.C. (the second phase of a comprehensive sustainability plan). This assessment incorporated granular data on built infrastructure and community resources (e.g., water and transportation infrastructure) and their functional importance in their relevant proximal areas towards spatial depictions of the impact of damage and disruptions of essential functions, which translates to high-level strategic planning efforts at the level of wards and priority planning areas (rather than to prescriptive plans that delegate plans to specific agencies and stakeholders, as seen in other cited efforts) (District Department of Energy & Environment [DOEE], 2016). This effort yielded a thoroughly integrated narrative, furthermore circumventing common data limitations, technical constraints, and logistical challenges by adopting a limited scope (with respect to the broader sustainability plan), leveraging proxy indicators, emphasizing system elements based on functions and populations (rather than assets), and thoughtfully synthesizing qualitative and quantitative analyses (rather than seeking a uniform spatial resolution from every analysis).

A more recent effort that demonstrates advancements in modeling tools is the 2021 vulnerability assessment from the Coastal Resilience Partnership of Southeast Palm Beach County, FL (formed in 2019 and comprising eight communities), which assessed vulnerabilities to a uniquely broad selection of climate-related hazards (12) among reviewed assessments embedded in adaptation planning efforts (Coastal Resilience Partnership, 2021). Due to this breadth, which includes less common considerations such as pest and disease outbreaks, assessment of each hazard involved significantly different approaches and scopes, which did not facilitate an analytical synthesis of climate-related threats. Where feasible, hazard-specific assessments mapped asset-level exposure and social vulnerability. Additional maps and discussions related to sensitivity describe potential implications of exposure of certain asset categories (e.g., commercial and industrial properties, grocery stores, and roads) to functions they enable. Due to historically traceable codes and standards relevant to flooding, adaptive

capacity of properties is estimated based on the first-floor elevation guidelines at the time of construction.

A relevant comparison can be made to a flood vulnerability assessment for Galveston, TX, for which a unique and historical lack of comparable standards presented numerous challenges (Feng et al., 2024).

Given how most of the reviewed non-HMP, climate-informed assessments are part of long-term planning efforts, the 2016 “Climate Ready Boston” vulnerability assessment is an example of a relatively early vulnerability assessment that has by now advanced into later stages of such an effort (City of Boston, 2016). As with Virginia Beach, it is also informed by prior engineering analyses of built infrastructure. The assessment includes sophisticated, model-driven, climate-informed, and scenario-based analyses of the vulnerability of people, buildings, infrastructure, and economic functions to flooding and extreme heat, providing detailed analyses that emphasize both assets and functions. This culminates in a comprehensive strategic plan for the city, including a science agenda, policy proposals, and action items that capture many notable features of previously described assessments, including prescriptiveness towards responsible stakeholders, specificity with respect to geographic or social targets, and integrated consideration for compounding threats.

Since 2016, local and regional agencies have expanded on these efforts with more specific vulnerability assessments, including with respect to public transit (Massachusetts Bay Transportation Authority [MBTA], n.d.) and stormwater outflows (Boston Water and Sewer Commission [BWSC], 2022).

What are key factors influencing an agency’s approach to a vulnerability assessment?

An agency’s approach to a vulnerability assessment is shaped by several key factors. Institutional capacity—often built through prior planning efforts—provides a foundation for more ambitious analyses. Financial resources and data availability, which vary by location and technical capability, also strongly influence the scope and depth of assessment activities. In some cases, formal mandates that exceed basic hazard mitigation planning (HMP) requirements, or the presence of specialized governmental functions (e.g., sustainability or resilience offices), enable broader and more integrated approaches.

Agencies may offset limitations in these core factors through strategies such as multi-jurisdictional collaboration, contracting external consultants, and adapting existing assessment frameworks. Other effective practices include focusing on broad system-level vulnerabilities, employing proxy indicators to address data or modeling limitations, and involving diverse stakeholders—both demographically and functionally—to enhance the relevance and integration of findings. Alignment with complementary local planning efforts (e.g., sustainability or climate action plans) can also significantly enhance effectiveness and uptake.

What key barriers prevent agencies from effectively conducting vulnerability assessments?

Table A.1 below summarizes key challenges and needs that commonly influence the scope, quality, and replicability of vulnerability assessments in for stormwater agencies. These insights are drawn from stakeholder interviews, primarily, and augmented with our review of local and regional assessments. Table A.1 categorizes barriers related to data, modeling, institutional capacity, regulatory context, and communication.

Table A.1 Key Challenges and Needs for Vulnerability Assessments

Category	Challenges and Needs
Data and Modeling Gaps	<ul style="list-style-type: none"> • Outdated or missing LiDAR, as-built surveys, and GIS layers • Lack of systematic flood data and stormwater asset inventory • Inconsistent datasets across jurisdictions (VA, MD, DC) • Need for integrated flood models capturing short- and long-duration events • Difficulty tracking/updating infrastructure improvements • Lack of tools to assess system vs. design capacity
Analytical and Technical Needs	<ul style="list-style-type: none"> • Improved tools/models to analyze: <ul style="list-style-type: none"> – GSI volume control and incremental effectiveness – Failure mechanisms and comparative effectiveness – Localized precipitation/microclimates – Vulnerabilities tied to development age • Need for dynamic, efficient modeling platforms • Tools for data synthesis and repetitive flooding hotspot identification
Regulatory and Planning Constraints	<ul style="list-style-type: none"> • New regulations emphasize volume control but limit site-scale flexibility • Lack of authoritative data sources hinders coordination • Cross-state regulatory/data alignment is difficult • Standardized (or otherwise common) practices for climate-informed local HMP development under 2022 guidance are still emerging or inconsistently applied
Capacity and Coordination Issues	<ul style="list-style-type: none"> • Limited staffing and technical capacity, especially in rural areas • Reliance on self-identified risks may overlook hazards • Need for cross-agency collaboration • Challenges aligning large organizations to shared frameworks
Financial and Risk Assessment Needs	<ul style="list-style-type: none"> • Limited ability to conduct financial risk assessments • Insufficient funding for data, modeling, and infrastructure upgrades • Unclear value propositions and lack of “right-sized” solutions
Communication and Framing Gaps	<ul style="list-style-type: none"> • Resilience often framed around compliance (e.g., CSO), not climate/flooding • Co-benefits of GSI underemphasized (e.g., social, ecological) • Need for consistent framing and education around vulnerability

Appendix B. Referenced Vulnerability Assessments

Table B.1 Hampton Roads Planning District Commission HMP (2022)

Overview and Use	
Location	Hampton Roads, Virginia
Summary	HMP jointly submitted by 19 cities and counties towards regulatory compliance, additionally demonstrating limited discussions of climate change. This assessment excludes quantitative or spatial analyses of stormwater.
Use	<p>As an HMP, this report ensures basic compliance with state and federal requirements, including for eligibility for grants (pre- and post-disaster) and for NFIP.</p> <p>This HMP exceeds basic compliance through limited discussions and analyses of the role of climate change in future vulnerability. It is additionally a strong example of an ambitious multi-government effort that pools the resources of relatively small communities and complements adjacent efforts.</p> <p>Though the process was led by stakeholders directly involved in emergency management functions, action items in the mitigation plan are individually delegated to a broad set of relevant agencies and stakeholders.</p>
Approach	
Assets/Functions Covered	<p>This HMP covers building stock, critical facilities, and populations.</p> <p>It proposes a definition of critical facilities: "those facilities or systems whose incapacity or destruction would present an immediate threat to life, public health, and safety or have a debilitating effect on the economic security of the region"</p>
Exposure	<p>This HMP does not attempt to quantify vulnerability to stormwater flooding, citing "insufficient and inconsistent data across the study area".</p> <p>The report spatially assesses exposure of asset inventory and populations to the 100-year floodplain, 500-year floodplain, storm surge zone (for a Category 3 hurricane), and flood way. The report additionally assesses exposure to SLR but not compounded with inland flooding.</p>
Sensitivity	<p>This HMP assesses the sensitivity of exposed assets based on estimates of potential losses to exposed assets and the social vulnerability of exposed populations.</p> <p>The sensitivity of the building stock is indirectly assessed through value of assets, construction materials, potential losses, and repetitive loss history. Potential losses incorporate building-level data such as age and first floor elevation.</p>
Adaptive Capacity	This HMP does not explicitly mention "adaptive capacity" but includes a capability assessment that identifies gaps between the mitigation plan and each community's regulatory and planning capabilities. This includes an inventory of completed actions and of existing plans, regulations, and programs.
Vulnerability Assessment	<p>Vulnerability assessments for the studied hazards included the identification of buildings, infrastructure, and populations potentially exposed to hazards based on current likelihood; the estimation of potential losses from each hazard; an inventory of historical incidents; and narrative descriptions of other relevant information such as the role of climate change and other nuances that were beyond the scope of HMP compliance (e.g., stormwater flooding).</p> <p>Findings from the vulnerability assessment were shared with stakeholders, which informed the development of a mitigation plan.</p>

Resources	
Data/Information	<p>12 of the cities and counties conducted user-defined facilities (UDF) analyses in 2019-2020, collecting detailed building information. This enabled use of HAZUS Level 2 analyses, yielding building-level estimates of potential loss from hazards. HAZUS Level 1 analyses were applied to 2 communities, relying on generalized national data.</p> <p>As typical for HMPs, FEMA floodplain maps were used to assess coastal and riverine flooding. Storm surge analyses leveraged NOAA's SLOSH tool.</p>
Workforce/Effort	<p>This effort was led by a steering committee comprised of representatives from the emergency management agencies (or equivalent) from each constituency, consultants (AECOM and Salter's Creek Consulting), and other stakeholders from relevant organizations.</p> <p>Additional support was provided by a large working group comprised of additional government stakeholders.</p> <p>As required in HMPs, this effort included the solicitation of the public and other stakeholders throughout the process.</p>
Contract Size	This effort was funded by a \$150,000 grant from FEMA through the Virginia Department of Emergency Management.
Time	Over 1 year between project kickoff (February 2021) and publication (June 2022).

Table B.2 Baltimore Disaster Preparedness and Planning Project (DP3) (2023)

Overview and Use	
Location	Baltimore, Maryland
Summary	Extended HMP that includes climate-informed assessment of future vulnerability and formal guidance for multi-hazard mitigation. This assessment excludes quantitative or spatial analyses of stormwater.
Use	<p>As an HMP, this effort ensures basic compliance with state & federal requirements, including for eligibility for grants (pre- and post-disaster) and for NFIP.</p> <p>Beyond its scope as an HMP, this report also serves as a "risk-reduction and climate adaptation plan" across the city, updating a prior 2018 effort with the same goals. As such, it discusses the role of climate change in all hazards based on projections and expert input. Action items, which include proactive climate adaptation efforts, are individually delegated to a broad set of relevant agencies and stakeholders.</p>
Approach	
Assets/Functions Covered	<p>This HMP covers general building stock (residential, commercial, and industrial), cultural & natural resources, critical facilities & infrastructure, and populations.</p> <p>As appropriate, narrative discussions of functions (e.g., in relation to community lifelines, energy, and transportation) are provided.</p>
Exposure	<p>This HMP does not attempt to quantify vulnerability to stormwater flooding.</p> <p>Exposure to coastal and riverine flooding was determined based on 100- and 500-year FEMA floodplain maps. The assessment also documents repeated loss areas.</p> <p>Exposure is also assessed for assets in projected SLR areas.</p>
Sensitivity	This HMP assesses the sensitivity of exposed assets based on estimates of potential losses to exposed assets and the social vulnerability of exposed populations.

	Sensitivity is also assessed for each hazard on a city-wide basis, reflecting the percent of the population exposed to a hazard, the percentage of property exposed to a hazard, and the loss estimate of a hazard relative to total replacement cost.
Adaptive Capacity	Adaptive capacity is evaluated for each hazard on a city-wide basis, reflecting whether "plans, policies, codes/ordinances in place and exceed minimum requirements; mitigation/protective measures in place; City has ability to recover quickly because resources are readily available, and capabilities are high." However, adaptive capacity is assessed as equal for all hazards such that it does not influence the ranking of hazards.
Vulnerability Assessment	This HMP is a broad exploration of hazards faced by the city, including in the context of climate change. To the feasible extent, the HMP includes spatial and quantitative analyses for each hazard, yielding consistent indicators for exposure and sensitivity. Additionally, climate change projections and relevant narrative discussions are provided for each hazard. Assessments of individual hazards inform a mitigation plan as well as a city-wide ranking of hazards that weighs exposure, sensitivity, adaptive capacity, and the role of climate change. This HMP includes narrative discussions of stormwater flooding (including in the contexts of climate change and compounding risks) in its sections on flooding, dam failure, coastal hazards, and severe storms. These discussions factor into the mitigation strategies detailed in the report.
Resources	
Data/Information	This HMP leverages HAZUS Level 2 to identify areas with high risk and potential loss from hazards. Building data was collected from Maryland Department of Planning. As typical for HMPs, FEMA floodplain maps were used to assess coastal and riverine flooding. SLR projections were provided by Eastern Shore Regional GIS Cooperatives. Nuisance flood projections were generated by NOAA for prior effort by Baltimore Office of Sustainability. Storm surge analyses leveraged NOAA's SLOSH tool.
Workforce/Effort	This HMP effort was led by a core planning team comprised of stakeholders from the Office of Sustainability, the Office of Emergency Management, Department of Planning, and Department of Public Works. The effort was supported by a large advisory committee comprised of stakeholders from local, state, and federal agencies as well as from community organizations. Additionally, support was provided by a social equity subcommittee. As required in HMPs, this effort included the solicitation of the public and other stakeholders throughout the process.
Contract Size	This effort was funded by a FEMA BRIC grant and the city (amount unknown).
Time	This effort was roughly 9 months long, between kickoff in February 2023 and adoption in November 2023.
Additional Information	
Notes	Report notes that "there is no official reporting system for the collection of data related to stormwater/urban flooding," which additionally limits ability to reflect on historical incidents.

Table B.3. GLISA FloodWise Communities Vulnerability Assessments (2021-2022)

Overview and Use

Location	4 Great Lakes Cities (Toledo, OH; Dayton, OH; Urbana, IL; Goshen, IN) ⁴
Summary	Climate change vulnerabilities assessments of stormwater in several Great Lakes cities based on a common GLISA framework, involving narrative, systems-based analyses of potential climate impacts.
Use	12 Great Lakes cities participated in the GLISA FloodWise Communities (FWC) pilot effort to develop a template for climate-informed vulnerability assessments in the context of stormwater management. FWC additionally aims to identify adaptation priorities as well as develop capacity within cities for future efforts and to foster multi-agency collaboration. These efforts complement other local efforts (for example, the 2022 Goshen, IN report aligns with the implementation plan defined in the 2016 Elkhart County, IN HMP).
Approach	
Assets/Functions Covered	Rather than relying on a comprehensive inventory of assets or functions, these assessments emphasize broad system elements including natural systems (incl. flood prone areas), built systems (incl. stormwater pipes, impermeable surfaces, and green infrastructure), social systems (incl. vulnerable populations), and emergency services. Selection of system elements is informed by expert and stakeholder input on known issues (in the case of Goshen, IN, selection was heavily informed by a major recent flooding incident) and SFHA flood maps.
Exposure	Exposure is assumed for the selected system elements. Narrative discussions of exposure describe potential impacts of climate change on the elements, potential roles of elements with respect to climate change-driven increases in stormwater flooding risks, and potential exposure of populations and assets (e.g., neighborhoods, commercial centers, community resources) in the proximity of the system element.
Sensitivity	Sensitivity reflects a qualitative rating on a scale of 0-4 for each system element that captures existing stressors to the element, potential impact of climate change on demand for the element, and any other factors that would make the element sensitive.
Adaptive Capacity	Adaptive capacity reflects a qualitative rating on a scale of 0-4 for each system element that captures whether the element is equipped to adapt to climate impacts and disruption from impacts, the changes necessary for adaptation, and whether existing stressors limit adaptability.
Vulnerability Assessment	Starting from high-level projections of changes to temperature and precipitation patterns, these vulnerability assessments involve qualitative analyses of system elements relevant to stormwater flooding based on history and stakeholder input. The relative sensitivity and adaptive capacity of system elements is then used to inform recommended next steps (e.g., capacity development, improved practices, or fundraising).
Resources	
Data/Information	The FWC framework leverages data on historical climate, climate projections, social vulnerability, and other relevant factors from the publicly available Neighborhoods at Risk tool.
Workforce/Effort	Multi-agency effort conducted in partnership with GLISA, Huron River Watershed Council, City of Ann Arbor, and Great Lakes Climate Adaptation Network.
Contract Size	Funded by NOAA Sectoral Applications and Research Program (SARP); funding amount unknown.

⁴ These four communities represent the vulnerability assessments reviewed by the research team and are only a subset of the FloodWise pilot. Twelve communities participated in the FloodWise Communities pilot program, including Ann Arbor, MI, Buffalo, NY, Cleveland, OH, Columbus, OH, Dayton, OH, Ferndale, MI, Goshen, IN, Grand Rapids, MI, Kalamazoo, MI, Madison, WI, Toledo, OH and Urbana, IL.

Additional Information	
Notes	The four communities reviewed here were part of the FloodWise Communities pilot program. Current offerings for this program may be different than the description here. More information on the program can be found at: https://glisa.umich.edu/engagement/floodwise-communities/ .

Table B.4 Washington, D.C. Vulnerability & Risk Assessment (2016)

Overview and Use	
Location	Washington, D.C.
Summary	Vulnerability and risk assessment built upon prior efforts to assess likely climate impacts in the region, including indirect assessment of stormwater vulnerability.
Use	<p>The aim is to inform future climate adaptation planning, with an emphasis on functions enabled by built infrastructure and community resources. The effort was intended to preclude a formal adaptation planning effort.</p> <p>The utilized methods are designed to be reusable by the city for future assessments.</p>
Approach	
Assets/Functions Covered	<p>This assessment covers built infrastructure (energy, transportation, water, and telecommunication), community resources (municipal resources, emergency services, medical services, human services, schools, and public housing), and populations.</p> <p>It excludes consideration of other residential and commercial infrastructure.</p>
Exposure	This assessment includes narrative discussions of precipitation projections but does not attempt to create stormwater flood depth maps. Instead, stormwater flooding exposure is assumed to align with SLR and storm surge flooding maps for 2020, 2050, and 2080.
Sensitivity	This assessment systematically considers the potential broad impacts to any given asset or function. "Each asset was ranked according to a qualitative assessment based on the extent of area of service loss, the estimated duration of service loss, the cost of damage, and impacts to public safety services, economic activities, public health, the environment, and to vulnerable populations."
Adaptive Capacity	<p>This assessment includes narrative discussions of adaptive capacity of built infrastructure and community resources, considering limited scenarios such as redundancy of medical services and availability of alternative modes of transportation. However, adaptive capacity is not discussed or quantified for most assets or quantified.</p> <p>Adaptive capacity of vulnerable populations is spatially assessed on a ward-level based on unemployment, educational attainment, and poverty prevalence.</p>
Vulnerability Assessment	This assessment emphasizes functions enabled by built infrastructure and community resources, utilizing quantitative and spatial methods to identify areas that are vulnerable to downstream effects of hazards that could impact these assets. These findings are qualitatively scored to rank ward-level vulnerability. These analyses lead to the identification of 5 priority planning areas with pronounced risks.
Resources	
Data/Information	<p>Data for location, service coverage, and construction costs of assets from the city and service providers (assets excluded where geospatial data is unavailable).</p> <p>Socioeconomic data at the ward level (based on prior Sustainable D.C. Plan effort).</p>

	Projections of climate impact from prior Climate Projections and Scenario Development Report).
Workforce/Effort	Prepared by consultants (Perkins+Will and Kleinfelder).
Contract Size	\$200,000 RFA from D.C. Department of Energy & Environment.
Additional Information	
Notes	Inundation maps for SLR and storm surge flooding (as a proxy for stormwater flooding) reflect 3 scenarios: 2020 (FEMA 100-year base flood map plus "known flood risk" areas based on repetitive loss data and areas near high-risk storm drains), 2050 (USACE Category 2 hurricane storm surge maps plus known flood risk areas), and 2080 (FEMA 500-year flood map plus known flood risk areas). "High-risk" storm drains are identified based on whether storm sewers are at or exceeding of capacity.
	Report states that vulnerability of natural systems is addressed in other efforts.

Table B.5 Town of Oxford & Talbot County Vulnerability Assessment (2016)

Overview and Use	
Location	Town of Oxford & Talbot County, Maryland
Summary	Integrated climate change vulnerability assessment, including indirect estimation of stormwater vulnerability, aimed at informing adaptation priorities.
Use	The primary aim of this report is to inform climate adaptation and related strategizing efforts in the region. The project involved development of an adaptable "framework for integrated vulnerability assessments" for "coastal communities facing the impacts of climate variability and change"
Approach	
Assets/Functions Covered	This assessment covers residential & commercial structures, populations, and subset of natural resources. The selection of natural resource categories was based on the likelihood of impact and economic valuation studies.
Exposure	Stormwater exposure determined from map of areas prone to hazard, based on elevation (> or < 2 feet), land cover (extent of development), and soil type.
Sensitivity	Structural vulnerability of residential & commercial buildings assessed on scale of 0-3 based on (1) building materials, (2) age of construction (i.e. before or after elevation requirements), and (3) grade of building (grades assigned by tax assessors are included in parcel data). Social vulnerability assessment based on 17-variable, census block-level index similar to SoVI. Adaptation priority score assigned based on "combination of risk analysis (surge and stormwater flooding impact per block) and vulnerability analysis (social and structural scores per block)."
Adaptive Capacity	Limited to non-prescriptive, narrative discussions of existing practices and opportunities to enhance adaptive capacity.
Vulnerability Assessment	This assessment vulnerability of assets based on proxies for stormwater flood risks, taking into account structural and social vulnerability based on granular, asset-level data. Scores are assigned based on structural and social vulnerability. Based on these scores, adaptation priorities were ranked on a scale of 1-4 at a block-level based on short-term (reflecting storm surge and stormwater flooding) and long-term (reflecting SLR and natural resource impacts) risks.

Resources	
Data/Information	"This work builds upon a range of NOAA methods and products (e.g., CSC's Digital Coast, National Marine Fisheries Service Social Indicators, NCCOS Community Well-being Indicators, NCCOS Hydrologic Modeling, and NCCOS Biogeographic Assessment Framework)." Given the goal of reusability, the assessment prioritizes data collected from national and state-level sources.
Workforce/Effort	Prepared by NOAA in 2016 with additional authors from the Town of Oxford and the MD Department of Natural Resources. Substantial stakeholder engagement with Town of Oxford, Talbot County, and State of Maryland.
Additional Information	
Notes	Report reflects input from Town of Oxford, including the ranking of "Stormwater & Flooding" as the climate impact of greatest concern.

Table B.6 Southeast Palm Beach County Vulnerability Assessment

Overview and Use	
Location	Southeast Palm Beach County, Florida
Summary	Multi-threat climate change vulnerability assessment for 8 jurisdictions in the region, including efforts to directly model stormwater vulnerability.
Type	
Use	Report describes adaptation strategies based on VA for the entire region and for each individual stakeholder. Assessment frames 6 types of adaptation: (1) infrastructure; (2) land use, zoning, building codes, and standards; (3) planning, policy, and management; (4) capacity building; (5) public outreach; and (6) funding and financing. Framework is designed for reusability for future efforts.
Approach	
Assets/Functions Covered	Spatial assessment of stormwater covers 7 categories of community assets and functions: (1) critical facilities, (2) water infrastructure, (3) economic factors, (4) natural resources, (5) people & socioeconomics, (6) property, and (7) roads & mobility. The water infrastructure category unique for its inclusion of green infrastructure.
Exposure	Exposure of assets determined based on exposure under each of 5 scenarios: 3 of 2020 baseline flood extent inundation (25-, 100-, and 500-year) and 2 of future conditions (100-year adjusted for SLR levels projected for 2040 and 2070).
Sensitivity	Sensitivity of assets designated as high if exposed and potential impact is high; medium if exposed and potential impact is low; and low if not exposed. Cited examples of assets with high potential impact are major medical facilities and apartment buildings with a large population.
Adaptive Capacity	Adaptive capacity of assets designated as high if constructed after 2017 (req. FFE at least 1 foot above BFE) or if not exposed; medium if constructed between 1982 and 2017 (req. FFE at BFE); or low if constructed before 1982.
Vulnerability Assessment	This report depicts spatial assessment of exposure, sensitivity, and adaptive capacity with respect to physical risks from rainfall-induced flooding based on scientific projections of rainfall depth and inundation. As relevant, the report details how factors such as social vulnerability (measured through SVI and other measures) and functions (e.g., economic functions, mobility, and service availability) intersect with physical vulnerability of assets.

The results of this multi-hazard assessment inform discussions of adaptation strategies and priorities for the whole region and for the individual participating communities.

Resources	
Data/Information	Scenarios for inundation are based on a 2020 baseline (25-, 100-, and 500-year) and on future conditions (100-year adjusted for 2040 and 2070 SLR projections). South Florida Water Management District (SFWMD) guidelines were used to determine design storm rainfall distributions for these scenarios. Rainfall depths for these distributions estimated using NOAA Atlas 14. Inundation maps were generated using Interconnected Channel and Pond Routing model (ICPR; now called "StormWise").
Workforce/Effort	SLR projections derived from prior regional effort. Stakeholders comprise Coastal Resilience Partnership (CRP) of Southeast Palm Beach County, a collaborative regional effort. Project team comprised of 8 working group members (representatives from 7 cities and 1 county within CRP), 4 external experts (from other Florida agencies), and 24 consultants (from 6 firms).
Time	Project conducted between April 2020 and June 2021. Report published in July 2021.
Additional Information	
Notes	Threats unrelated to flooding are not treated with the same level of comprehensiveness (with respect to assets & functions) and often apply narrative (rather than spatial) analyses.

Table B.7 Complementary Efforts from Boston (2015-2024)

Overview and Use	
Location	Boston, Massachusetts
Summary	Several complementary climate vulnerability assessment efforts, including innovative efforts to directly model stormwater vulnerability in the context of climate change and climate adaptation.
Use	These reports broadly inform stormwater management and climate adaptation planning in the city, serving as an example of successful interagency cooperation and capacity development that has built upon foundational efforts towards more advanced efforts over approximately a decade. This is demonstrable through the 2021 HMP (unique among cited HMPs for its reliance on existing results) and recent efforts from the Boston Water and Sewer Commission (BWSC) and Massachusetts Bay Transportation Authority (MBTA), all of which adhere to a common framework.
Approach	
Assets/Functions Covered	Assets include buildings, critical facilities, natural resources, and populations. Functions include coastal outfalls and public transportation services.
Exposure	Analysis of stormwater considers scenarios of 10-year, 24-hour design storms under current and projected future conditions. Inundation maps based on these design storms integrate the projected impacts of climate change on precipitation, SLR, and storm surge. The exposure of assets is assessed based on intersection with inundation maps. The exposure of functions is assessed based on knowledge of areas with elevated stormwater flooding risk under design storms.
Sensitivity	The sensitivity of assets reflects an ensemble of indicators of physical damage, social impacts, and function disruption in exposed areas.

	The sensitivity of outfalls is based on simulated discharge volume, simulated flood area, invert elevation, size, and relationship to transit, critical facilities, vulnerable populations, and economic functions.
Adaptive Capacity	Approaches to analyzing adaptive capacity are not described in substantial detail in these reports. However, they note that identified action plans are prioritized based on knowledge of adaptive capacity, leveraging informed input from stakeholders and communities.
Vulnerability Assessment	<p>These reports also serve as an exceptional example for science-based integrated assessments of stormwater.</p> <p>The 2016 "Climate Ready Boston" report includes a projection-driven vulnerability assessments of assets and functions to heat, stormwater flooding, and coastal and riverine flooding. This report utilizes both spatial and narrative analyses to describe multiple dimensions of vulnerability at asset-, population-, and function-levels. Based on results, stakeholders were interviewed to develop resilience initiatives (comprising 11 strategies within 5 layers).</p> <p>Subsequent efforts enhance models and yield more prescriptive (and often agency-specific) adaptation plans in alignment with the identified resilience initiatives.</p>
Resources	
Data/Information	Data and models used to develop design storms and inundation maps include Massachusetts Coast Flood Risk Model (MC-FRM), NOAA historical climate data, IPCC projections, and the PCSWMM modeling platform.
	Efforts share a common baseline design storm, leveraging additional scenarios as appropriate.
Workforce/Effort	Reports authored by various local government agencies with support from other government agencies, regional academic researchers, community stakeholders, and consultants.
Time	The collected reports depict roughly a decade of efforts.
Additional Information	
Notes	<p>Compilation of Vulnerability Assessments:</p> <p>Boston Water and Sewer Commission (2015; citation only)</p> <p>"Climate Ready Boston" (2016)</p> <p>Massachusetts Bay Transportation Authority (2018)</p> <p>Boston HMP (2021)</p> <p>Boston Water and Sewer Commission (2023)</p> <p>Massachusetts Bay Transportation Authority (2024)</p>

Appendix C. Data Resources for Carrying out a Vulnerability Assessment

The following two tables provide guidance on data use in vulnerability assessments. Table C.1 is an overview of examples of how historical and projected datasets can be used to inform a vulnerability assessment, based on each approach included in this document. Table C.2 is a resource of datasets that agencies can use to carry out their own vulnerability assessment.

Table C.1 Historical and Projected Data in Vulnerability Assessments

Approach	Example of Historical Data Use	Example of Projected Data Use
Expert Judgement	Experts draw on local experience of past flooding, stormwater system failures, or community response to extreme rainfall to identify current vulnerabilities.	Panels or workshops incorporate climate projections—such as more frequent high-intensity rainfall or sea level rise—to discuss how future conditions could affect known trouble spots.
Scorecards	Assets are scored based on past incidents, maintenance records, or documented damages from previous storms.	Future hazard scenarios (e.g., projected rainfall changes or increased flood frequency) are used to adjust exposure or sensitivity scores for planning horizons of 2050 or 2100.
Indicators	Indicators include values like infrastructure age, historical flood claims, or observed impervious area growth to capture baseline exposure and sensitivity.	Climate projections (e.g., modeled changes in precipitation, temperature, or runoff) are integrated as future indicator variables, helping identify how vulnerability may shift over time.
Spatial Analysis	GIS layers of historical flood extents, inundation reports, or stormwater service calls are overlain with asset maps to visualize exposure patterns.	Modeled floodplain extents or inundation maps generated from climate and sea level rise projections illustrate future exposure zones and potential expansion of flood-prone areas.
Statistical Analysis	Historical event and damage data are used to estimate hazard probabilities and relationships between rainfall and system performance.	Downscaled climate model projections adjust rainfall intensity-duration-frequency (IDF) curves or event likelihoods to estimate future probabilities and impacts.
Modeling	Hydrologic and hydraulic models are calibrated using observed rainfall-runoff data and known flood events to simulate current system behavior.	Models are run with projected climate inputs (e.g., future storm intensities, sea level rise, or altered land use) to estimate system performance and potential future vulnerabilities.

Table C.2 Datasets for Use in Vulnerability Assessments

Data Category	Source/Tool	Description	Example(s)	Exposure	Sensitivity	Adaptive Capacity
Building/Infrastructure Data & Tools	Building Diagrams	Structural data including first floor elevation, age, and other characteristics	HRPDC HMP 2022		X	X
Building/Infrastructure Data & Tools	Parcel and Tax Data	Source of data that can inform inventory of building stock, value, and structural characteristics.	Baltimore HMP 2023 Talbot County, MD 2016	X	X	X

Building/Infrastructure Data & Tools	Codes and Standards	Where data is limited, codes and standards can inform assumptions about building characteristics (e.g., first floor elevation) based on known information (e.g., year of construction)	Talbot County, MD 2016 Southeast Palm Beach County, FL 2021		X	X
Building/Infrastructure Data & Tools	Google Street View	Used to obtain first floor elevation estimates (where data cannot be obtained through records or assumptions)	HRPDC HMP 2022 Galveston, TX 2018		X	X
Building/Infrastructure Data & Tools	Aerial Imagery	Aerial imagery for use in collecting or updating building data; sources include Bing, Google, and state agencies	Boston 2016	X		
Building/Infrastructure Data & Tools	Private Data Sources	Data managed by private owners with relevance to vulnerability (e.g., telecommunications, energy, paved surfaces, housing developments)	Washington, D.C. 2016 Boston 2016	X	X	X
Building/Infrastructure Data & Tools	Other Public Data Sources	Data managed by public agencies can inform inventory and structural analysis of building and infrastructure (e.g., public transit, stormwater infrastructure, utilities)	Boston 2016-2024 GLISA FWC 2021-2022	X	X	X
Social Data & Tools	CDC Social Vulnerability Index (SVI)	Index based on 16 indicators, for use at county or census tract level	Baltimore HMP 2023 Southeast Palm Beach County, FL 2021		X	X
Social Data & Tools	Social Vulnerability Index (SoVI)	County-level index based on 29 indicators	South Carolina 2023		X	X

Social Data & Tools	FEMA National Risk Index (NRI)	Calculates risk based on expected annual loss, social vulnerability, and community resilience metrics for 18 natural hazard categories	HRPDC HMP 2022		X	X
Social Data & Tools	Decennial Census	Includes demographic and housing data for many potential analytical purposes.	Baltimore HMP 2023 Washington, D.C. 2016 Talbot County, MD 2016	X	X	X
Social Data & Tools	American Community Survey (ACS)	Additional demographic data estimated annually by the U.S. Census Bureau based on surveys; includes data not included in Decennial Census (e.g., education, employment)	Baltimore HMP 2023 Talbot County, MD 2017	X	X	X
Social Data & Tools	Bureau of Labor Statistics	Potentially relevant demographic data (e.g., occupations, wages, unemployment)	HRPDC HMP 2022	X	X	X
Social Data & Tools	County Vital Records	Potentially relevant demographic data	Talbot County, MD 2016	X	X	X
Social Data & Tools	NOAA Community Social Vulnerability Indicators (CSVI)	Community-level data connecting social vulnerability, climate change, and commercial and recreational fishing	Talbot County, MD 2016	X	X	
Social Data & Tools	EASI Demographics	Source of potentially useful data such as geographic estimates of medical illness rates	Boston 2016		X	
Social Data & Tools	Other Public Data Sources	Other public data that could inform social vulnerability (e.g., public and assisted housing, SNAP retailers)	Southeast Palm Beach County, FL 2021		X	X

Social Data & Tools	Neighborhoods at Risk Tool	Free, interactive database for identifying neighborhoods that may be vulnerable to wildfire, flooding and extreme heat at local, county and state levels.	GLISA FWC 2021-2022	X	X
Flood Data & Tools	FEMA Floodplain Maps & Flood Insurance Studies (FIS)	These sources delineate Special Flood Hazard Areas (SFHA), characterize local flood hazards, and identify probable exposure to coastal, riverine, and storm surge flooding (including through Flood Insurance Rate Maps; FIRM)	HRPDC HMP 2022 Southeast Palm Beach County, FL 2021	X	
Flood Data & Tools	NWS SLOSH Model	Projections of storm surge hazard areas and inundation levels related to hurricanes	HRPDC HMP 2022	X	
Flood Data & Tools	Other Public Data Sources	Data managed by public agencies can include historical data on floods and stormwater	Boston 2016-2024	X	
Flood Data & Tools	Interconnected Channel and Pond Routing (ICPR or "StormWise") Modeling	Modeling tool to estimate likely inundation areas based on projected rainfall distributions	Southeast Palm Beach County, FL 2021	X	
Flood Data & Tools	Personal Computer Storm Water Management Model (PCSWMM)	Modeling tool to project extent and duration of flood inundation	Boston 2023	X	
Climate Data & Tools	NOAA Atlas 14	Data and projections of precipitation frequency informed by climate models	Southeast Palm Beach County, FL 2021	X	
Climate Data & Tools	NOAA National Centers for Environmental Information (NCEI)	Broad repository for environmental and climate data (e.g., historical precipitation and drought)	Southeast Palm Beach County, FL 2021	X	

Climate Data & Tools	National Climate Assessment (NCA)	Authoritative source of climate projections	Southeast Palm Beach County, FL 2021	X	X	X
Climate Data & Tools	Intergovernmental Panel on Climate Change (IPCC)	Authoritative source of climate projections	Boston 2023	X	X	X
Climate Data & Tools	LOCA Downscaled Projections	Statistically downscaled IPCC CMIP6 climate projections of North America at 6km resolution		X		
Climate Data & Tools	Applied Climate Information System (ACIS)	NRCC-maintained tool for managing historical and real-time climate data for decision-making		X		
Other/Multi-category Data & Tools	NOAA Digital Coast	Source of useful data, including geospatial sea level rise projections and high resolution (up to 1m) land cover data (C-CAP)	Talbot County, MD 2016	X		
Other/Multi-category Data & Tools	U.S. Army Corps of Engineers (USACE) Data	Source of various data and projections, including for sea level rise, storm surge, and regional studies of flood damage models.	Washington, D.C. 2016	X		
Other/Multi-category Data & Tools	Hazus Level 1	Loss estimates based on generalized assumptions	HRPDC HMP 2022	X	X	
Other/Multi-category Data & Tools	Hazus Level 2	Loss estimates based on local data (e.g., first floor elevations) and generalized assumptions	HRPDC HMP 2022 Baltimore HMP 2023	X	X	
Other/Multi-category Data & Tools	Hazus Level 3	Loss estimates based on detailed engineering data		X	X	
Other/Multi-category Data & Tools	USGS National Land Cover Database	High resolution (up to 30m) database on land cover categories (e.g., urban, level of development, wetlands)	Baltimore HMP 2023 Southeast Palm Beach County, FL 2021	X		

Other/Multi-category Data & Tools	Homeland Infrastructure Foundation-Level Data (HILFD)	Geospatial data on U.S. critical infrastructure	Baltimore HMP 2023	X	X	X
Other/Multi-category Data & Tools	EPA Comprehensive Environmental Response, Compensation and Liability Information System (CERCLIS)	Data on superfund sites (sites with high potential loss due to pollution)	Baltimore HMP 2023		X	
Other/Multi-category Data & Tools	Eastern Shore Regional GIS Cooperative	Hosts various sea level rise and flooding projection datasets	Baltimore HMP 2023	X		
Other/Multi-category Data & Tools	Natural Resource Studies	Data and estimates from government, academic, and other sources such as economic valuation of natural resources (e.g., wetlands, beaches, green infrastructure) or ecological surveys.	Talbot County, MD 2016	X	X	X
Other/Multi-category Data & Tools	USGS National Map Viewer	Tool and data source for viewing and downloading geospatial data (e.g., land elevation)	Talbot County, MD 2016	X		
Other/Multi-category Data & Tools	USDA National Resources Conservation Service (NRCS) Soil Data	Geospatial soil data for most U.S. counties; uses include indicators related to water infiltration and runoff potential	Talbot County, MD 2016	X	X	
Other/Multi-category Data & Tools	ESRI Business	Source of potentially useful geospatial data, including sales volume and employee count for estimation of economic impact	Beaufort, SC 2019		X	
Other/Multi-category Data & Tools	IMPLAN Software	Economic decision-making tools, including for estimation of business interruption due to hazards	Boston 2016		X	

Other/Multi-category Data & Tools	SHELDUS	County-level dataset to explore frequency and consequences of various natural hazards		X	X
Other/Multi-category Data & Tools	Remote Sensing Data	Data collected using remote sensing technologies (e.g., LANDSAT, LIDAR) with relevance to vulnerability (e.g., vegetation, impervious surfaces, land subsidence, building and ground elevation)	Boston 2016 HRPDC HMP 2022 GLISA FWC 2021-2022	X	X

Abbreviations

BMP	Best Management Practice
CAP	Climate Adaptation Partnership
CDC SVI	Centers for Disease Control Social Vulnerability Index
EPA	United States Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FWC	FloodWise Communities
GIS	Geographic Information System
GLISA	Great Lakes CAP/RISA Team
HMP	Hazard Mitigation Plan
HRPDC	Hampton Roads Planning District Commission
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
MARISA	Mid-Atlantic CAP/RISA
MBTA	Massachusetts Bay Transportation Authority
MS4	Municipal Separate Storm Sewer System
NFIP	National Flood Insurance Program
NPDES	National Pollutant Discharge Elimination System
NOAA	National Oceanic and Atmospheric Administration
RISA	Regional Integrated Sciences and Assessments
SVF	System Vulnerability Factor
SWMP	Stormwater Management Program
TMDL	Total Maximum Daily Load
USGS	United States Geological Survey
VRA	Vulnerability and Risk Assessment

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