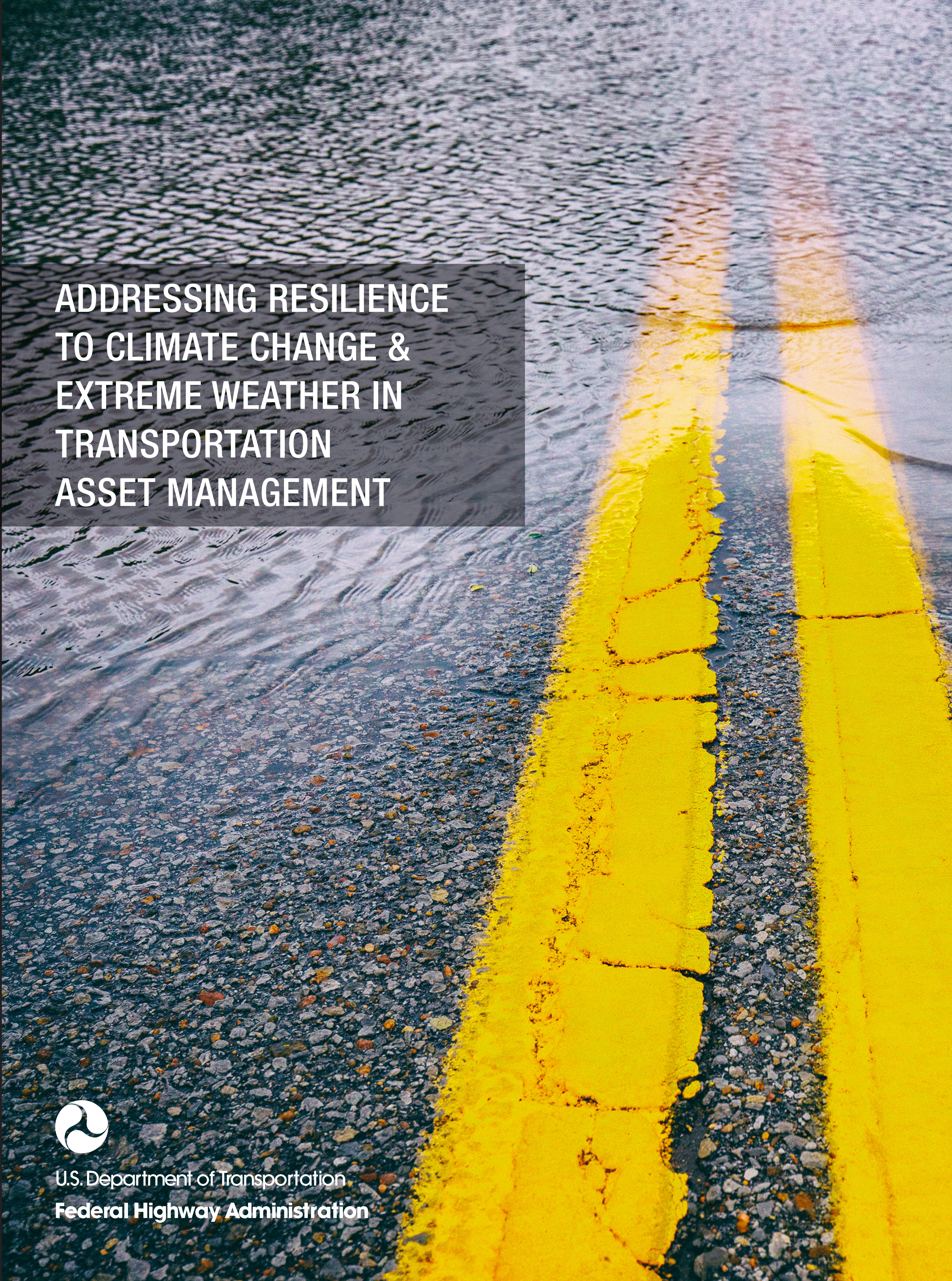

ADDRESSING RESILIENCE TO CLIMATE CHANGE & EXTREME WEATHER IN TRANSPORTATION ASSET MANAGEMENT

U.S. Department of Transportation
Federal Highway Administration

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This project was carried out in support of 23 U.S.C. § 503(b)(3)(B)(viii), which directs the Department of Transportation "to carry out research and development activities … to study vulnerabilities of the transportation system to … extreme events and methods to reduce those vulnerabilities."

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This handbook is designed to help transportation practitioners incorporate natural hazard resilience into asset management. Upfront, it summarizes who to include in this planning process and how different groups (e.g., asset management, environment) can work together on this topic. The handbook then explains how to develop a baseline understanding of the transportation networks’ exposure and vulnerability to extreme weather and climate change. This understanding lays the groundwork for the integration of resilience into asset management. From there, the handbook steps through the core elements of an asset management plan, providing ideas and emerging practices on how to consider natural hazard resilience in the asset inventory, the performance gap assessment, asset management objectives and targets, the risk management process, life-cycle planning, investment strategies and financial plans, and information on monitoring risks over time. An appendix includes case studies on a series of State Department of Transportation pilots on incorporating resilience into asset management.</td></tr>
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ACRONYMS

Federal, State, and Regional Transportation Organizations

ADOT	Arizona Department of Transportation
Caltrans	California Department of Transportation
CAMPO	Capital Area Metropolitan Planning Organization (Texas)
CDOT	Colorado Department of Transportation
FHWA	Federal Highway Administration
KYTC	Kentucky Transportation Cabinet
MassDOT	Massachusetts Department of Transportation
MDOT SHA	Maryland Department of Transportation State Highway Administration
MnDOT	Minnesota Department of Transportation
NJDOT	New Jersey Department of Transportation
NOACA	Northeast Ohio Areawide Coordinating Agency
NYSDOT	New York State Department of Transportation
ODOT	Oregon Department of Transportation
PennDOT	Pennsylvania Department of Transportation
RIDOT	Rhode Island Department of Transportation
TDOT	Tennessee Department of Transportation
TxDOT	Texas Department of Transportation
USDOT	U.S. Department of Transportation
VTrans	Vermont Agency of Transportation
WSDOT	Washington State Department of Transportation

Other

BCSI	Bridge and Culvert Sensitivity Index
CFR	Code of Federal Regulations
CMIP	Coupled ModFel Intercomparison Project
DEM	Digital Elevation Models
DOT	Departments of Transportation
ER	Emergency Relief
FEMA	Federal Emergency Management Agency
GIS	Geographic Information System
LiDAR	Light Detection and Ranging Tool (surveying method)
LRTP	Long Range Transportation Plan
MAP-21	Moving Ahead for Progress in the 21st Century Act (P. L. 112-141)
MaPIT	Massachusetts Project Intake Tool
MPO	Metropolitan Planning Organization
NBI	National Bridge Inventory
NEPA	National Environmental Policy Act
NGO	Non-governmental Organization
NHS	National Highway System
NOAA	National Oceanic and Atmospheric Administration
NRCS	National Resources Conservation Service
NWS	National Weather Service

RCP	Representative Concentration Pathway
SLR	Sea Level Rise
SMART	Specific, Measurable, Agreed, Realistic, and Time-Bound Objectives
SOGR	State of Good Repair
STIP	Statewide Transportation Improvement Plan
TAMP	Transportation Asset Management Plan
USGS	U.S. Geological Survey
VAST	Vulnerability Assessment Scoring Tool

GLOSSARY

The following definitions are provided solely for the purposes of this handbook unless the definition is accompanied by a citation.

Adaptation – Adjustment in natural or human systems in anticipation of or response to a changing environment in a way that effectively uses beneficial opportunities or reduces negative effects.

Adaptive Capacity – The asset or system's ability to adjust, repair, or flexibly respond to damage caused by extreme weather events or changing environmental conditions. For example, alternative routes that could be used to reach the same location would increase adaptive capacity compared to a route that lacks redundancy.

Asset – All physical highway infrastructure located within the right-of-way corridor of a highway. The term asset includes all components necessary for the operation of a highway including pavements, highway bridges, tunnels, signs, ancillary structures, and other physical components of a highway. 23 CFR 515.5.

Asset Class – Assets with the same characteristics and function (e.g., bridges, culverts, tunnels, pavements, or guardrails) that are a subset of a group or collection of assets that serve a common function (e.g., roadway system, safety, Intelligent Transportation (IT), signs, or lighting). 23 CFR 515.5.

Key Term Usage

Asset management teams and environmental practitioners may use different terms for similar concepts. Because this handbook may benefit a variety of audiences, establishing a common vocabulary can be beneficial. For example, the following terms are often used by various groups to indicate the same ideas:

- Vulnerability and Risk: commonly used to refer to an asset or system's inability to cope with physical impacts.
- Adaptation and (Risk) Mitigation: commonly used to refer to actions that lessen potential adverse impacts of physical hazards.

Asset Life – Encompasses various terminology used by agencies to describe the lifespan of an asset, such as useful life or service life.

Asset Management – A strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the life-cycle of the assets at minimum practicable cost. 23 CFR 515.5.

Asset Sub-Group – A specialized group of assets within an asset class with the same characteristics and function (e.g., concrete pavements or asphalt pavements.) 23 CFR 515.5.

Current and Future Environmental Conditions – (as used in 23 CFR 515.7(c)(1)), includes extreme weather events, climate change, seismic activity.

Exposure – Refers to an asset or system that is located in an area experiencing or is likely to experience direct effects of current and future environmental conditions, including gradual changes in climate and extreme weather events. For example, an exposed road could experience more frequent tidal inundation due to its location in a low-lying area.

Extreme Events – Risks posed by gradual changes in the climate and extreme weather events. The definition does not apply to other uses of the term nor include consideration of risks to the transportation system from other natural hazards, accidents, or other human induced disruptions. (FHWA Order 5520 - Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events | Federal Highway Administration (dot.gov))

Extreme Weather Events – Significant anomalies in temperature, precipitation and winds and can manifest as heavy precipitation and flooding, heatwaves, drought, wildfires and windstorms (including tornadoes and tropical storms). Consequences of extreme weather events can include safety concerns, damage, destruction, and/or economic loss. Changing environmental conditions can also cause or influence extreme weather events. (FHWA Order 5520 - Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events | Federal Highway Administration (dot.gov))

Hazard (or Natural Hazard or Stressor) – A natural event with the potential to cause substantial damage or gradual deterioration, such as hurricanes, extreme precipitation, flash flooding, wildfire, droughts, sea level rise, loss of permafrost, and high heat.

Mitigation – Reduction in risks through adjustments in natural or human systems in anticipation of or response to a changing environment.

Preparedness – Actions taken to plan, organize, equip, train, and exercise to build, apply, and sustain the capabilities necessary to prevent, protect against, ameliorate the effects of, respond to, and recover from extreme weather events related damages to life, health, property, livelihoods, ecosystems, and national security.

Project-Level/Asset-Level – Refers to singular assets such as bridges or pavement sections.

Resilience – The ability to anticipate, prepare for, or adapt to conditions or withstand, respond to, or recover rapidly from disruptions, including the ability-

(A)(i) to resist hazards or withstand impacts from weather events and natural disasters; or

(ii) to reduce the magnitude or duration of impacts of a disruptive weather event or natural disaster on a project; and

(B) to have the absorptive capacity, adaptive capacity, and recoverability to decrease project vulnerability to weather events or other natural disasters.

23 U.S.C. 101(a)(24); *see also* FHWA Order 5520 - Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events | Federal Highway Administration (dot.gov))

Risk – The positive or negative effects of uncertainty or variability upon agency objectives. 23 CFR 515.5. In the context of resilience, risks are often assessed as a product of the likelihood that an asset will experience a particular stressor, and the consequence.

Risk Management –The processes and framework for managing potential risks, including identifying, analyzing, evaluating, and addressing the risks to assets and system performance. 23 CFR 515.5. The process for developing a risk management plan involves assessing and prioritizing risks according to their likelihood of occurrence and potential consequence. *See* 23 CFR 515.7(c).

Sensitivity – How the asset or system responds to or is affected when exposed to current or future environmental conditions, including gradual changes in climate and extreme weather events. For example, a tunnel could be more sensitive to flooding due to challenges removing water.

Transportation Asset Management Plan (TAMP) – The term TAMP in this handbook is the risk-based asset management plan that is required under 23 U.S.C. 119(e) and is intended to carry out asset management as defined in 23 U.S.C. 101(a)(2). Asset management plan means a document that describes how a State DOT will carry out asset management as defined in 23 CFR 515.5. This includes how the State DOT will make risk-based decisions from a long-term assessment of the National Highway System (NHS), and other public roads included in the plan at the option of the State DOT, as it relates to managing its physical assets and laying out a set of investment strategies to address the condition and system performance gaps. The TAMP describes how the highway network system will be managed to achieve State DOT targets for asset condition and system performance effectiveness while managing the risks, in a financially responsible manner, at a minimum practicable cost over the life-cycle of its assets. 23 CFR 515.5.

Targets – Used in a general sense in this document as relevant to asset management and may include required Federal performance targets under 23 U.S.C. 150(d).

Vulnerability – The degree to which an asset or system is susceptible to, or unable to cope with adverse effects of current and future environmental conditions, including gradual changes in climate and extreme weather events. In the transportation context, vulnerability is a function of a transportation system's exposure to natural hazards and changing environmental conditions, sensitivity to stressors, and adaptive capacity.

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Executive Summary

This handbook provides information to State DOTs and other agencies on how to use asset management processes to make transportation systems more resilient to current and future environmental risks. Extreme weather events and climate change impacts can damage transportation infrastructure and exceed the functional capacity of a facility, leading to unplanned and intolerable service disruptions. Additionally, gradual changes in temperature and precipitation can change infrastructure deterioration rates and result in increased costs due to decreased asset lifespans, emergency repairs, increased maintenance and labor costs, supply chain disruptions and lost economic activity. The Fourth National Climate Assessment (NCA4) noted that climate change is expected to raise the cost of building and maintaining transportation infrastructure in the U.S., though cost increases will vary by region depending on the level of impacts experienced (USGCRP, 2018).

Why use this handbook?

The impacts of a changing climate (such as higher temperatures, sea-level rise, and changes in seasonal precipitation and the intensity of rain events) and extreme weather events are affecting the lifecycle of transportation systems and are expected to intensify (FHWA, 2014c). As climate change intensifies, the frequency and severity of risks related to extreme weather events are expected to worsen over time and negatively affect transportation infrastructure, though impacts will vary by region (USGCRP, 2018) and transportation asset, and in some cases may be positive. Addressing the risks associated with extreme events (both climate change and extreme weather events) through asset management can help reduce them; meet agency asset management objectives and targets; and extend the service life of highways, bridges and other assets. Proper planning for extreme weather events and climate change at the asset and system levels provides a variety of benefits, such as minimizing disruptions to the transportation system, reducing agency and user costs, and decreasing risks to public safety, as well as reducing maintenance costs (FHWA, 2018a).

Integrating Resilience into the TAMP

Note: Throughout this handbook, Federal requirements related to the asset management practices covered in each chapter are referenced in yellow text boxes. These yellow text boxes also indicate where a best practice might contribute to compliance with 23 U.S.C. 119(e) and relevant regulations.

This handbook was developed prior to the Bipartisan Infrastructure Law (BIL), enacted as the Infrastructure Investment and Jobs Act (Pub. L. No. 117-58) in 2021. Accordingly, this handbook does not directly address implementation of the BIL amendment that requires State DOTs to consider extreme weather and resilience in Transportation Asset Management Plan (TAMP) lifecycle cost and risk management analyses (23 U.S.C. 119(e)(4)(D)). However, this handbook may still be useful to State DOTs as a general resource on addressing transportation resilience to extreme weather events and climate change more broadly, and FHWA expects the information provided to have continued relevance as State DOTs work to implement the BIL amendment. The relevant regulations are:

1. *Process for Establishing the Asset Management Plan.*
    - Requires State DOTs to "develop a risk-based asset management plan that describes how the National Highway System (NHS) will be managed to achieve system performance effectiveness and State DOT targets for asset condition, while managing the risks, in a financially responsible manner, at a minimum practicable cost over the life cycle of its assets." *(See* 23 CFR 515.7).
    - DOTs are specifically required to consider "current and future environmental conditions, such as extreme weather events, climate change, and seismic activity" in the risk management plan. (*See* 23 CFR 515.7(c)(1)).
    - DOTs should also consider these risks when developing the life cycle plan and financial plan which could influence investment strategies. (*See* 23 CFR 515.7(b) and (d)).

2. *Periodic Evaluation of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events* (*See* 23 CFR Part 667)
    - Requires State DOTs to determine if there are reasonable alternatives to roads, highways, and bridges that have required repair and reconstruction activities on two or more occasions due to emergency events. (*See* 23 CFR 667.1).
    - State DOT TAMP risk management processes must take into account the Part 667 risk-based evaluations (*See* 23 CFR 515.7(c)(1)) and include the results of those evaluations for NHS pavements and bridges in the TAMP (*See* 23 CFR 515.9((d)(3) and (6)).

Who should use this handbook?

This handbook is designed primarily for State DOT personnel who are developing the federally required transportation asset management plans (TAMPs) under 23 CFR part 515 or otherwise involved in transportation asset management, and staff at other agencies focused on asset management processes and resilience.

What does this handbook cover?

This handbook provides approaches, strategies, and examples of addressing risks related to extreme weather and climate change in asset management. It describes opportunities to address risks associated with current and future environmental conditions, natural hazards, sea level rise, and extreme weather events. The handbook also provides practical options to integrate resilience into short- and long-term asset management practices to help optimize investment decisions. The following sections describe the core chapters of the handbook.

ASSEMBLING THE RIGHT TEAM

Chapter 2: Engage Stakeholders and Assemble the Right Team explains how building support across relevant departments and stakeholders could facilitate the integration of current and future environmental risks into agency asset management plans and processes. Consider implementing any or all of the following steps to assemble the right team:

- **Designate a risk manager** to validate the effort and ensure progress is made.
- **Define clear roles and responsibilities** to limit duplicative efforts and hold responsible parties accountable for meeting their obligations.
- **Use internal communications** to discuss how current and future environmental considerations fit into different departments and why it is important to plan for and address these risks collaboratively.
- **Keep leadership informed** on how risks are affecting the agency; this can help secure the support and resources needed to make significant progress toward addressing risks in asset management plans.
- **Coordinate and collaborate with external stakeholders** to enable more efficient collection and assessment of key information while limiting duplicative efforts.
- **Communicate effectively** to build support and gain valuable input for addressing risks through asset management planning.
- **Coordinate particularly with at risk communities** -- such as disadvantaged communities that may lack resources to address climate impacts, or those facing more dire climate change impacts.

ASSESSING THE IMPLICATIONS OF CURRENT AND FUTURE ENVIRONMENTAL RISKS

Chapter 3: Understand Vulnerability to Extreme Weather Events and Climate Change explains how an agency may conduct a vulnerability assessment. Assessing vulnerability to current and future environmental conditions is a key foundational step for integrating these risks into asset management. Vulnerability assessments can range in scope, in terms of both the transportation assets and key climate variables considered. The FHWA's Vulnerability Assessment and Adaptation Framework provides a process for conducting a vulnerability assessment and examples of how different agencies have applied aspects of that process in practice.

To better understand a transportation system's vulnerabilities, consider the following questions:

- **What are the relevant risks?** Gather information on historical performance, agency knowledge, infrastructure design standards, and guidelines to determine which environmental conditions have the greatest effects on the transportation network, both now and in the future.
- **How are the risks changing?** Review historical information to understand the relationship between past damages and associated conditions and determine key thresholds for climate variables relevant to risks in the region. Collect and review data on expected future environmental conditions caused by a changing climate to understand the frequency and severity of risks to transportation, both now and in the future.
- **How resilient is the transportation system?** Use data on relevant risks from current and expected future environmental conditions, along with other information, to conduct a vulnerability assessment using a stakeholder input approach, indicator-based desk review approach, and/or project-level assessment.
- **What changes to this approach to climate change/ extreme weather vulnerability assessment may be appropriate for asset management?** Modify the vulnerability assessment approach to obtain the best-suited outputs for the asset management planning process.

Addressing Resilience in Asset Management Processes

Chapters 4 through 10 provide recommendations on how to integrate resilience into the asset management process and asset management practices and policies. These chapters focus on identifying specific entry points for addressing current and future environmental conditions and conclude with a wrap-up discussion of action items from the chapter. Each chapter also contains a yellow text box that discusses how the information and examples in the chapter can be considered by State DOTs when developing the federally required TAMP.

Key Transportation Asset Management and Resilience Integration Chapters

This handbook presents opportunities to address resilience at all steps in the asset management process in the order they are typically completed. However, some of the asset management planning steps have a stronger link to resilience than others, including:

- *Chapter 7: Establish Risk Management Process*
- *Chapter 8: Develop Life Cycle Plan*
- *Chapter 9: Establish Resilient Investment Strategies and Financial Plans*

Asset Inventory

Chapter 4: Develop Asset Inventory explains that an asset inventory provides an opportunity to identify assets that are vulnerable to current and future environmental conditions so their unique considerations can be carried through the entire transportation asset management planning process. The vulnerability assessment can inform an agency's understanding of which assets have been damaged by extreme weather in the past and how future environmental conditions could affect asset conditions in the future. As part of this inventory, consider establishing hazard categories to reflect vulnerability to current and future environmental conditions. When determining the asset/hazard categories that can best support asset management, consider the environmental hazards that:

- Have the potential to result in catastrophic damages to assets during extreme weather events. For example, storm surge in combination with other factors, such as sea level rise or other climate change effects, has the potential to damage low lying infrastructure, including bridges, in coastal areas. Sea level rise can facilitate increased damage and/or cause storm surge to reach further inland, potentially impacting more assets.
- Are more likely to result in slow but notable increases in asset deterioration due to gradual changes in temperature, precipitation, sea level rise, and other environmental conditions.
- May affect a large enough number or percentage of the individual assets within an asset class to have potential consequences to the transportation system.
- May reduce system performance or impact the ability to achieve desired targets.

For example, the hazard categories could include:

- High sea level rise vulnerability: Pavements and bridges located in future inundation areas.
- High inland flooding vulnerability: Bridges and approaches in locations where the bridge hydraulic opening affects flood elevation (*i.e.*, the backwater potential is high) and/or where flood discharges are expected to increase because of increased precipitation.

Consider including in the TAMP: Observed performance gaps due to environmental conditions.

If the agency's analysis indicates that environmental conditions may contribute to difficulties in meeting agency performance targets, consider including a description of these findings in the performance gap write-up in the TAMP.

Consider including in the TAMP: Hazard categories to reflect vulnerability to current and future environmental conditions.

In developing the federally required TAMP, it may be helpful to develop categories of vulnerable assets for inventory and asset condition reporting. Table 0-1 depicts a simplified summary table that includes example hazard categories for the highest priority vulnerabilities. These hazard categories can combine asset categories with the hazard(s) of most concern (i.e., most likely to result in catastrophic damages or increases in asset deterioration).

Table 1-1: Example Inventory and Condition Summary Table With "Hazard Category" Column (Outlined in Red)

Asset Class	Asset Sub-Group	Hazard Category	Inventory			Asset Condition		
			Units	Quantity	Lane Miles or Square Meters	% Good	% Fair	% Poor
Bridges	Moveable	High inland flood vulnerability						
	Timber	High sea level rise vulnerability						

Performance Gap Assessment

Chapter 5: Conduct Performance Gap Assessment explains how to use a performance gap analysis to determine if agency identified performance gaps are due to damages related to extreme weather events. For example, start by identifying the lowest-performing assets that are adversely impacting the performance of the system and determining if there may be an extreme weather event-related cause for the low performance. To determine if there is an extreme weather event-related cause, engage knowledgeable staff, review previously completed vulnerability assessment findings (*Chapter 3: Understand Vulnerability to Extreme Weather Events and Climate Change*), and compare the findings with the vulnerability categories created as part of the asset inventory *(Chapter 4: Develop Asset Inventory*).

Objectives, Measures and Targets

Chapter 6: Set Resilience Objectives, Measures and Targets describes a process for including risks from extreme weather events and climate change in setting the strategic direction of the transportation asset management process. Consider incorporating resilience to extreme weather events and climate change by:

- **Modifying existing objectives, measures and targets**: If existing objectives, measures and targets for the transportation asset management process are infeasible or inappropriate given future environmental conditions, consider modifying these existing objectives, measures, and targets to better reflect expected changes in environmental conditions.

- **Developing new objectives, measures and targets**: Consider working with stakeholders to develop new or additional resilience-related objectives, measures, and targets. This is particularly important when vulnerable assets are included in asset management analyses.

Agencies can also consider aligning the objectives, measures and targets of the asset management planning process to other planning documents, such as those outlined in the long-range transportation plan, to ensure consistency across various planning documents.

Consider including in the TAMP: Specific objectives, measures and targets to address risks from extreme weather events and climate change.

Consider modifying existing objectives, measures and targets if they are likely to become infeasible under future environmental conditions. In addition, if existing objectives, measures and targets do not adequately measure or account for climate change, consider developing new resilience-related targets for vulnerable assets to better measure progress toward increasing resilience.

Risk Management

Chapter 7: Establish Risk Management Process describes the risk management process and how it and the vulnerability assessment complement resilience efforts. The chapter describes flexible strategies for conducting both the vulnerability assessment and the broader risk management assessment so that the agency considers them both in the asset management analyses. The risk management chapter suggests agencies:

- **Develop short-term and long-term approaches**: Some risks have immediate impacts such as floods or slope failures. Reacting to these risks occurs quickly, though adapting to the risks may take a long time, depending on the type of adaptation (improving culvert maintenance/cleaning is quicker than building or elevating a bridge or mitigating landslides) Other risks such as sea level rise are more chronic and, in some cases, may gradually affect assets. Both types of risks should be monitored, their impacts considered, and their mitigation factored into short-term and long-term risk-management strategies.
- **Compare natural hazard risks to other risks:** Evaluating environmental risks in a consistent manner with other agency risks allows for an apples-to-apples decision process regarding when, where, and how much to invest in risk mitigation strategies.
- **Influence life-cycle and investment strategies:** The risk assessment also can be an important input to the life-cycle strategies and investment strategies for mitigating risks.

Consider including in the TAMP: A list of risk mitigation strategies for the top-priority risks.

Develop proactive and reactive risk mitigation strategies. Organize mitigation strategies in a risk register table that includes the top risks, likelihood, impact, risk owner, and risk mitigation strategy. Note that one risk event can cause a variety of impacts, which may warrant a series of risk statements and mitigation strategies.

Life-cycle Plan

Chapter 8: Develop Life-cycle Plan describes how life-cycle planning can be enhanced with an improved understanding of how weather-related events will influence assets throughout their life-cycle. Understanding expected future temperature, rainfall, and sea level rise can inform decisions about how assets may perform, what maintenance activities may need to be increased, and whether assets are properly classified within the environmental categories in pavement and bridge management systems. The life-cycle plan chapter suggests:

- **Classify assets within management systems:** Some management systems allow the classification of assets within environmental or other categories. Over time as temperature or rainfall events worsen, agencies may need to shift assets into the appropriate categories or explore new approaches for integrating these risks into management systems. This will allow management systems to more accurately predict performance.
- **Address future conditions when making long-term investments:** Asset management plan analyses lead to decisions about how to maintain, preserve and improve assets or replace them at the end of their useful life. Agencies can make more informed decisions by considering the effect of weather-related conditions over the service lives of existing and planned assets.

Consider including in the TAMP: Life cycle planning strategies that address current and future environmental conditions.

Describe the new actions the agency will take to integrate resilience to future environmental conditions into life cycle decisions. Utilize the 23 CFR Part 667 evaluation results to identify assets particularly prone to damage from extreme events.

Investment Strategies & Financial Plans

Chapter 9: Establish Resilient Investment Strategies and Financial Plans discusses how investment strategies and financial plans are the place where the preceding risk and life-cycle decisions and analysis influence how the agency allocates its resources to keep its assets resilient. Investment strategies and financial plans can reflect natural hazard resilience strategies by:

- **Reflecting objectives, measures and targets:** The investment strategies can provide the resources to achieve the agency's objectives, measures, and targets related to managing extreme weather risks.
- **Closing gaps and funding at-risk assets:** Investment strategies can consider what resources are needed to close condition gaps, and to maintain the assets within the inventory that contribute most to resilience.
- **Investing in strategies to reduce risks:** Funding the strategies that increase resilience and decrease threats, while capitalizing on opportunities, is another important element of investment strategies. It is important to consider the full service life of the asset (two to

seven decades) when selecting the appropriate strategies. The financial plan will then focus on actions needed in the time period covered by the plan.

Consider including in the TAMP:

Possible investment strategies for vulnerable assets. Identify strategies that can be used for categories of assets identified as at risk due to current and future environmental conditions. Each category of assets may have a separate investment strategy.

A strategy for proactively addressing resilience. Develop a strategy for proactively addressing the resilience of assets included in the TAMP through normal capital investment or dedicated funding streams. Include an estimated budget for additional maintenance required due to increases in the frequency or intensity of extreme weather events. Include an estimated budget to mitigate subgroups of assets in the TAMP that are highly vulnerable.

Monitoring Plan

Chapter 10: Develop a Monitoring Plan to Track Risks Related to Extreme Weather and Climate Change discusses the importance of monitoring plans for keeping resilience strategies current and addressing changing extreme weather patterns and environmental conditions. It describes steps such as:

- **Updating the risk register:** The risk register includes the identified threats, as well as the strategies the agency selected to manage those threats. Making the risk register a frequently reviewed and updated tool can support the monitoring of resilience strategies.
- **Tracking changes in the asset inventory:** Updating the asset inventory and condition data is another way to monitor if the conditions of at-risk assets are performing as expected.
- **Tracking vulnerability indicators**: Monitoring and reassessing vulnerability indicators can help an agency stay informed of risks.
- **Integrating strategies into other plans and programs:** If resilience strategies influence plans and programs, the monitoring of program development and project delivery can be a means to monitor if strategies are being implemented.

Consider including in the TAMP: Process for tracking strategies to address risks from current and future environmental conditions.

Develop a plan for monitoring the effectiveness of any risk mitigation strategies as well as identifying changing risks from current and future environmental conditions.

1 INTRODUCTION

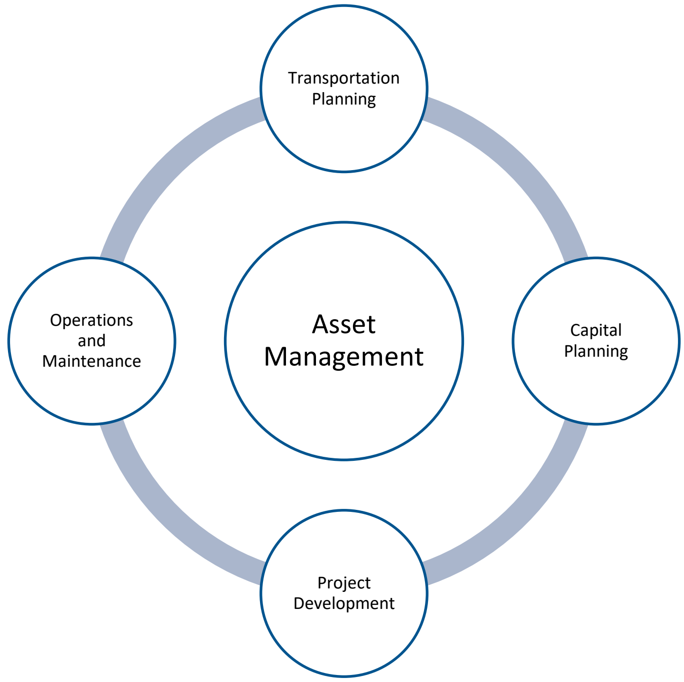


Figure 1-1. Asset management informs the transportation life cycle.

Asset management provides a process to (better) manage the transportation system to increase performance and reduce risks and costs. Climate change and extreme weather threats can shorten asset life spans, require additional emergency repairs, and raise labor and materials costs for transportation agencies. More frequent impacts can reduce economic activity and disrupt supply chains. These threats can also pose safety concerns for the traveling public, raise travel times, and delay shipments of goods. Events such as extreme temperature changes can reduce pavement life and floods can damage or shorten the life of pavements, structures and other assets. While transportation providers have been building and managing roadway assets to withstand natural hazards since at least the Roman Empire, current day transportation agencies are seeing these threats magnified by climate change, and we can expect these additional threats to transportation to worsen over the coming decades. The Fourth National Climate Assessment (NCA4) notes that climate change is expected to raise the cost of building and maintaining transportation infrastructure in the U.S., though cost increases will vary by region depending on the level of impacts experienced (USGCRP, 2018) and asset, and in some cases may be positive.

Repairs to damaged infrastructure have already been costly, and we can expect them to increase with climate change in coming decades. In December 2021, the Federal Highway Administration (FHWA) allocated $1.4 billion in Emergency Relief Program funds for 42 States, American Samoa, Puerto Rico, U.S. Virgin Islands, and tribal governments to repair roads and bridges damaged by recent extreme events (USDOT 2021). This figure does not include all of the applications submitted for emergency relief funds, further emphasizing that extreme weather events are a large and costly issue that affects many DOTs now and could affect more as environmental conditions change.

The cost implications of extreme events, defined as climate change and extreme weather events, warrant a robust analysis of and defense against these risks (FHWA, 2014c). Extreme weather events and climate change are projected to increase the costs of maintaining, repairing, and replacing infrastructure. There are more than 60,000 miles of U.S. roads and bridges in coastal floodplains that cost billions to repair and maintain in the face of extreme storms and hurricanes

(Jacobs, et al., 2018). Similarly, extreme precipitation events regularly shut down parts of the Interstate Highway System for days or weeks due to flooding and landslides, as happened in the first five months of 2017 in California (I-80 and I-880) in January, north central California (I-5) in February, and Idaho (I-86) in March. Similarly, flooding took place in the central United States including Missouri (I-44 and I-55), Iowa, Nebraska and Oklahoma in May 2019. Costs from extreme heat events are also significant (Jacobs, et al., 2018). For example, the 2011 heat wave cost the Texas Department of Transportation $26 million in pavement damage (Jacobs, et al., 2018).

To address the requirements established by 23 U.S.C. 119, FHWA issued regulations (23 CFR Part 515) pertaining to risk-based transportation asset management plans (TAMPs) that include consideration of the impact of current and future environmental conditions. This handbook often refers to asset management plans but is useful for asset management practices in general.

1.1 Why Use This Handbook?

This handbook is designed to provide a practical set of options for integrating resilience to extreme weather events and climate change into asset management practices and policies to help optimize investment decisions and promote sustainable infrastructure. (Sustainability, including GHG emission reductions, is a factor that could be more fully addressed in asset management practices in the future.) The overarching goal of an asset management program is to minimize costs and maintain a state of good repair while maximizing performance over the life-cycle of assets. Transportation agencies should consider how extreme weather events and climate change may increase costs. Additionally, agencies should consider information on extreme weather events and climate change that could impact whole-of-life costs of assets such as changes to deterioration rates or interference with the operational performance of assets.

This handbook distinguishes between **damage** and increased **deterioration** caused by extreme weather events and rising temperatures, increased precipitation, or other changing environmental conditions. Damage can include the immediate loss of intended performance of a facility, while deterioration can include the gradual loss of performance. Expenditures for repairs or replacement projects may increase to address damage from extreme weather events. Projects may be designed to repair damage, harden assets or replace assets to be more resilient to climate change or to reduce service impacts where it is not possible to redesign to withstand a greater event economically. Solutions to adapt damaged infrastructure to extreme weather events and climate change should be suitable for the community and surrounding infrastructure to minimize impacts and maintain local connections. Increased maintenance efforts may be another response to event-related damage. Damage-related expenditures may appear in investment strategies and financial plans as responses to the expected increasing number or likelihood of damaging events. Investment strategies to respond to actual or likely damage could take the form of programs to increase the resilience of structures, raise low-lying roadways, or enhance drainage assets, for example. Deterioration is more gradual and may be addressed more incrementally in the life-cycle planning process. Over time, increased deterioration may involve increased investments to offset it. However, because increased deterioration caused by extreme weather events and climate change may be realized more slowly, actions to address deterioration may not be reflected in near term investment strategies. Increased deterioration should be captured in the asset life-cycle and accounted for (as increased maintenance, repair, or replacement) in future expenditures.

Planning for extreme weather events and climate change at the asset and system levels can produce the following benefits (FHWA, 2018a):

- Minimize disruptions to the transportation system.
- Decrease the financial impacts of extreme weather events and climate change on transportation agencies as well as the larger transportation network and economy.
- Improve an agency's ability to achieve its mission and objectives.
- Decrease impacts to public services such as emergency services, public safety, and quality of life.

While this handbook was developed prior to the BIL amendment that requires State DOTs to consider extreme weather and resilience in TAMP lifecycle cost and risk management analyses (23 U.S.C. 119(e)(4)(D)), there are existing Federal regulations that require State DOTs to consider risks related to resilience in their TAMP and FHWA expects the information in this handbook will have continued relevance as State DOTs implement the BIL amendment. The FHWA asset management regulations in 23 CFR 515.7: *Process for establishing the asset management plan* require State DOTs to "develop a risk-based asset management plan that describes how the National Highway System (NHS) will be managed to achieve system performance effectiveness and State DOT targets for asset condition, while managing the risks, in a financially responsible manner, at a minimum practicable cost over the life-cycle of its assets." In doing so, each State DOT is required to develop processes for several components including the following:

- Performance gap analysis (23 CFR 515.7(a))
- Life-cycle plan (23 CFR 515.7(b))
- Risk management plan (23 CFR 515.7(c))
- Financial plan (23 CFR 515.7(d))
- Investment strategies (23 CFR 515.7(e))

Pursuant to existing regulations, State DOT asset management processes for developing the risk management plan must identify "current and future environmental conditions, including extreme weather events," (23 CFR 515.7(c)(1)) and should include information on extreme weather events and climate change in the life-cycle plan (23 CFR 515.7(b)) (see textbox).

In addition to these requirements, the TAMP summary of the condition of NHS pavements and bridges must be informed by the evaluations from 23 CFR Part 667 (23 CFR 515.9(d)(3)): *Periodic Evaluation of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events.* Section 23 CFR 667.1 states that State DOTs "shall conduct statewide evaluations to determine if there are reasonable alternatives to roads, highways, and bridges that have required repair and reconstruction activities on two or more occasions due to emergency events." Emergency events is defined in 23 CFR 667.3. The term can include declared emergencies caused by extreme weather events, such as flooding.

Asset Management Regulatory Provisions on Current and Future Environmental Conditions

Risk Management Plan: 23 CFR 515.7(c)(1) requires State DOTs to develop a risk management process that identifies risks that can "affect condition of NHS (National Highway System) pavements and bridges and the performance of the NHS, including risks associated with **current and future environmental conditions, such as extreme weather events, climate change**…and risks related to recurring damage and costs as identified through the evaluation of facilities repeatedly damaged by emergency events carried out under part 667 of this title."

Life Cycle Plan: 23 CFR 515.7(b) requires State DOTs to establish a life cycle planning process for an asset class or asset sub-group that should "include future changes in demand; information on current and future environmental conditions including **extreme weather events, climate change**…and other factors that could impact whole of life costs of assets."

[As of October 21, 2021, State DOTs are required to consider extreme weather and resilience as part of the lifecycle cost and risk management analyses within a State TAMP (23 U.S.C. 119(e)(4)(D)). As noted in the Executive Summary, this handbook does not address implementation of this provision from the BIL.]

1.2 WHO SHOULD USE THIS HANDBOOK?

Primary users – State DOT personnel who manage transportation assets and are involved in developing asset management plans as well as other staff focused on asset management processes and resilience.

Other users – Staff who provide or exchange information with asset managers and TAMP developers, such as planning, project development, and maintenance and operations.

Other transportation agencies or asset owners—e.g., metropolitan planning organizations (MPOs), local transportation agencies or transit owners—that develop or implement transportation asset management programs may find the handbook useful for addressing extreme weather events and climate change. Even MPOs with no asset ownership can find value in this handbook to help them coordinate planning and programming for local agencies that own assets in their region. MPOs also may find this handbook useful for identifying strategies to link resilience to planning processes, such as the long-range plans, or to short-term programming priorities.

Practice Tip: Engage Broadly

To develop a robust and effective transportation asset management program, consider engaging a variety of individuals and stakeholders throughout the process. To facilitate engagement on current and future environmental conditions, consider sharing this handbook with them. Stakeholders include:

- Leadership
- Transportation system management team
- Pavement
- Bridge
- Maintenance and operations
- Environment
- Planning

See *Chapter 2: Engage Stakeholders and Assemble the Right Team* for more information about how to build support across various departments and stakeholders.

1.3 WHAT RESOURCES WERE USED TO DEVELOP THIS HANDBOOK?

This handbook is based on literature on integrating extreme weather considerations into asset management plans, the results of a number of State TAMPS, and by FHWA-supported asset management and resilience pilot studies, including:

- **Arizona DOT (ADOT)** –This pilot is part of an ongoing work program through which ADOT plans to address the following stressors through the life-cycle planning of roadway assets and asset classes: intense precipitation, system flooding, wildfires, wildfire-induced floods, drought-related dust storms, and rockfall incidents (ADOT, 2019).
- **Kentucky Transportation Cabinet (KYTC)** – This pilot analyzed the potential impacts of extreme heat and extreme precipitation on pavements and bridges using a screening tool for identifying bridge sensitivity to flooding and a methodology for incorporating climate projection data into pavement design and performance monitoring (Kentucky Transportation Cabinet, 2019).

- **Massachusetts DOT (MassDOT)** – This pilot used proxy variables estimated at the state scale to perform an initial flood resilience screen for MassDOT bridges and culverts (MassDOT, 2019).
- **Maryland DOT State Highway Administration (MDOT SHA)** – This pilot refined and expanded a vulnerability assessment of state assets to climate hazards and identified and implemented specific opportunities to integrate the vulnerability assessment results into existing MDOT SHA asset management, planning, and other processes (MDOT SHA, 2019).
- **New Jersey DOT (NJDOT)** – This pilot focuses on impacts to the reliability of the roadway from precipitation events and assesses the vulnerability of culverts and drainage systems by focusing on road closures due to flooding events (NJDOT, 2019).
- **Texas DOT (TxDOT)** – This pilot developed and applied a framework for understanding and integrating extreme weather risk into asset management using Houston as a case study (TxDOT, 2019).

See the **Appendix** for summaries of each of these studies.

1.4 What does this handbook cover?

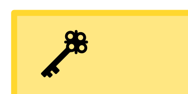
Addressing resilience to extreme weather events and climate change can be an integral element of each step of the asset management process. This handbook provides approaches, strategies, and examples of integrating these risks into asset management planning. **Chapter 2** focuses on assembling the right team to build support, work together, and streamline the information-gathering and decision-making processes.

Chapter 3 focuses on understanding the transportation system's vulnerability to extreme weather events and changing environmental conditions. Understanding vulnerability sets the foundation for integrating risks into the asset management process.

Chapters 4 through 10 provide recommendations on how to address resilience in each step of an asset management plan development process and asset management practices and policies. These chapters identify specific entry points for integrating extreme weather events and climate change into each step, and conclude with a summary checklist of action items from the chapter:

- Chapter 4 – Asset Inventory
- Chapter 5 – Performance Gap Assessment
- Chapter 6 – Objectives, Measures and Targets
- Chapter 7 – Risk Management Process
- Chapter 8 – Life-cycle Plan
- Chapter 9 – Investment Strategies and Financial Plan
- Chapter 10 – Monitoring Plan

Within Chapters 4 through 10 the yellow textboxes with the key icon (shown at right) summarize key recommended inputs to the federally required TAMP. These textboxes are intended to provide a succinct snapshot of key entry points for incorporating extreme weather events and climate change into the TAMP.



In addition, the **appendix** provides summaries of the asset management and extreme weather pilots.

Key TAMP Integration Chapters

This handbook presents opportunities to address resilience at all steps in the asset management process in the order they are typically completed. However, **some of the asset management planning steps have an important link to resilience**, including:

- *Chapter 7: Establish Risk Management Process*
- *Chapter 8: Develop Life Cycle Plan*
- *Chapter 9: Establish Resilient Investment Strategies and Financial Plans*

Even though agencies may take different approaches tailored to their unique needs and circumstances, this handbook is designed to help agencies accelerate the integration of resilience in asset management.

Integrating Resilience into Other Aspects of Transportation

In addition to this handbook, FHWA offers a number of resources on integrating resilience into other aspects of the transportation system:

- *Incorporating Risk Management into Transportation Asset Management Plans* (FHWA, 2017b)
- *Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance* (FHWA, 2015a)
- *Synthesis of Approaches for Addressing Resilience in Project Development* (FHWA, 2017d)
- *Integrating Resilience into the Transportation Planning Process: White Paper on Literature Review Findings* (FHWA, 2018b)

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2 Engage Stakeholders and Assemble the Right Team

Building support across a variety of relevant departments and stakeholders can help facilitate the integration of current and future environmental risks into asset management processes. Asset management plans address risks ranging from finances, to adequate staffing, to making risk-based tradeoffs between asset classes. In many agencies, the person or team with the most expertise on current and future environmental risks does not sit within the asset management group. These teams should work together to effectively integrate resilience into asset management processes and plans. This chapter focuses on practices for engaging stakeholders and building a culture of resilience by outlining steps such as the identification of a risk manager and communication between agency departments and leadership to facilitate current and future environmental risk-related information sharing and coordination. While the steps described in the following subsections are not required, agencies may find them beneficial.

2.1 Identify a Risk Manager for Addressing Resilience in Asset Management

Transportation agencies may wish to assign an individual or team to integrate current and future environmental risks into asset management. A designated risk manager is especially important if resilience is a new concern for an agency. The role of the risk manager is to motivate and serve as a central resource for collaboration between asset management and resilience-focused staff. The risk manager is likely to be someone already working on or familiar with risks associated with current and future environmental conditions and/or asset management.

2.2 Define Roles and Responsibilities

To keep efforts on track, consider defining clear roles and responsibilities for specific individuals or departments to limit duplicative efforts and hold responsible parties accountable for meeting their obligations. If multiple departments or teams are involved, it may be useful to present options for defining the roles and responsibilities of each team (e.g., asset management team, environmental team, planning team, etc.), such as:

- Gather key stakeholders to establish goals and objectives for this effort to ensure all members are on the same page.
- Assign goals or objectives to specific teams based on their expertise and interest. Within each group, assign tasks based on individual strengths and expertise. Establish deadlines and allocate resources as necessary to ensure tasks are achieved. For example, the environmental team may be tasked with collecting data on extreme weather events and climate change and assessing how risks to the transportation system may change. The asset management team may be tasked with collecting the inventory of existing asset conditions to identify potentially vulnerable assets. Together, these two teams may then discuss which assets are most at risk due to climate change.
- Hold regular meetings with the full team to monitor and discuss progress, identify challenges that another group may be better suited to address, and minimize duplicative work.

Defining roles and responsibilities is also important to delineate how the resilience effort complements the overall risk-based asset management processes. *Chapter 7: Establish Risk Management Process* addresses how resilience is integral to an agency's risk management processes. A number of organizational strategies are possible to link the resilience-related risk efforts with the larger risk management process, but they generally fall into one of two strategies. The resilience effort can be a subset of the larger risk management effort, or the resilience risk-management effort can be the primary risk management function that also incorporates other risks often associated with managing assets.

2.3 Promote cross-departmental collaboration

Both asset management- and resilience-focused efforts break down traditional silos and involve collaboration and coordination across multiple departments. By integrating resilience into asset management, an agency may engage departments that traditionally have not worked together on these issues. For example, the environment department may not have formerly been involved in asset management. However, to fully integrate extreme weather resilience into the asset management process, the environment department should be consulted.

Transportation agencies can use internal communication methods such as trainings or working sessions to discuss how different departments address extreme weather events and climate change and why it is important to plan for and address these risks collaboratively. Increasing awareness can help build support across different departments for collectively addressing these risks and sharing data and information across departments. Agency examples include:

- The MDOT SHA asset management pilot found that working sessions were effective for raising awareness and brainstorming ideas to address these risks in asset management and other decision-making processes (MDOT SHA, 2019).
- The Caltrans asset management pilot established a technical advisory group to review project progress, contribute to vulnerability and adaptation rankings, and contribute ideas and knowledge to the overall process. The technical advisory group, which was made up of local transportation planning agencies, provided expertise and local knowledge to Caltrans' District 1 Climate Change and Vulnerability Pilot Study (Caltrans, 2014; FHWA, 2015b).
- Many FHWA-sponsored resilience pilots have worked with maintenance and engineering staff to collect data and information on current and future environmental conditions and asset conditions, such as WSDOT (WSDOT, 2011), MnDOT (MnDOT, 2014), CAMPO (CAMPO, 2015), TDOT (TDOT, 2015), MassDOT (MassDOT, 2015), and NYSDOT (NYSDOT, 2015).

2.4 Communicate with leadership

Leadership should be aware of risks resulting from climate change and extreme weather events. Keeping leadership informed on the potential impacts of these risks can build top-level support to allocate resources for addressing these risks. Establish regular methods of communication to help ensure the paths for dialogue between leadership and staff remain open.

Possible approaches to elevating environmental condition-related risks, when warranted, include:

- Provide a briefing on top risks every quarter, creating opportunities to address these risks.
- Provide a 1–2-page memo of high-level findings on work related to these risks and their importance to keep leadership aware of and engaged with ongoing work.
- When discussing these risks with leadership, tie the discussion back to the agency goals, objectives, or costs so they can better understand the potential impact. Ensure leadership is aware of the benefits of addressing identified risks in life-cycle planning and financial plans.

2.5 Coordinate with External Stakeholders

External stakeholders can provide knowledge, data, and potential experience addressing extreme weather events and climate change. Coordinating and collaborating with external stakeholders can allow agencies to more efficiently collect and assess information related to environmental conditions and limit duplicative efforts. It may also be useful to coordinate with at risk communities -- such as disadvantaged communities that may lack resources to address climate impacts, or communities more directly exposed to climate change impacts due to their location. For climate data in particular, there are likely already resources available from external stakeholders that can provide the type of data needed. For example, Federal data sets or existing local climate vulnerability assessments (see *Chapter 3: Understand Vulnerability to Extreme Weather Events and Climate Change* for more information) may serve as relevant resources.

Potential External Stakeholders

External stakeholders can be a key resource for understanding and addressing current and future environmental conditions, including:

- MPOs
- Locally owned NHS
- Transit owners
- Local or state government
- Federal government agencies (e.g., USGS)
- Universities
- Local or regional NGOs
- At risk communities

For the TxDOT asset management pilot, coordinating with other agencies and external stakeholders to acquire flood risk data was essential to developing the agency's vulnerability assessments (TxDOT, 2019). In many cases, the data and models TxDOT were looking for already existed. TxDOT held a stakeholder meeting at the beginning of the project to identify what information stakeholders had and how it could be of use to TxDOT and the other stakeholders in the room. By working collaboratively, TxDOT was able to build stronger relationships with many stakeholders and use existing data to predict and mitigate flooding.

Many pilots set up advisory groups to engage stakeholders and vet data and approaches throughout their projects. For example, the role of the Caltrans technical advisory group was to review project progress, contribute to vulnerability and adaptation rankings, and contribute ideas and knowledge to the overall process (Caltrans, 2014).

2.6 Communicate Effectively

Communicating effectively, whether to internal departments, leadership, stakeholders, or the public is crucial to building support and gaining valuable input. Many of the communication strategies described below can also apply to the development and distribution of an asset management plan. Asset management plans are public documents and represent an opportunity for agencies to communicate risks to both internal and external stakeholders. Components such as risk management, life-cycle planning, and financial planning provide opportunities to clearly demonstrate how risks percolate throughout asset management.

Possible approaches for communicating about current and future environmental risks include:

- **Keep the message positive.** Focus messaging on the positive and what can be done to plan for and address these risks.
- **Tailor the message to the audience.** Different audiences have different interests and roles in addressing climate risks. For example, for leadership, a high-level overview of the risks and how to address them is warranted. For internal departments or stakeholders and potential partners, a more detailed explanation of the risk, the knowledge gaps, and the role of each department or stakeholder in addressing the risk may be more appropriate.
- **Tie the discussion back to agency goals, objectives, or costs.** Goals and objectives can drive decision-making across an agency. Conveying how risks associated with extreme weather events and climate change can affect an agency's ability to meet its goals and objectives and framing the risks in terms of costs can be useful. For example, the costs of adding resilience considerations to existing projects that address another issue may be less expensive and more efficient than funding a project solely focused on resilience improvements. In addition, inaction may be most costly for assets that experience accelerated deterioration due to climate change.
- **Acknowledge uncertainty and challenges inherent in addressing environmental conditions.** Understanding uncertainty in climate change data is a common challenge. In some cases, it may be helpful to cite historical extreme weather events to demonstrate observed and potential impacts to assets, and to explain that past rare events may become more common in the future. Recent extreme events can be more tangible to understand.
- **Balance the focus on risk with engagement around solutions**. Highlight multiple benefits, especially those in the near term, and consider identifying how addressing risks from extreme weather events and climate change may create other benefits. For example, improving stormwater drainage infrastructure to be more resilient to changing precipitation patterns may provide an opportunity to improve infrastructure so it is safer for pedestrians in the near-term as curbs, gutters, drains, and sidewalks are improved.

Potential Avenues for Effective Communication

- Elevator pitch
- Briefing memos
- Presentations
- Data visualization tools
- Working sessions

- **Develop concise talking points.** Develop a short- and high-level pitch on how and why it's important to consider both current and future environmental risks in asset management.

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3 Understand Vulnerability to Extreme Weather Events and Climate Change

This chapter explains how to determine if components of the transportation system are vulnerable to extreme weather events such as hurricanes, floods, extreme heat, Nor'easters, and climate change effects such as sea level rise This chapter covers key elements of vulnerability assessments most relevant to asset management, lists resources for conducting vulnerability assessments, and describes approaches to determine:

- Relevant hazards (*Section 3.1*),
- Changes in relevant hazards (*Section 3.2*),
- Resilience of the transportation system (*Section 3.3*), and
- How to organize vulnerability assessment outputs for asset management (*Section 3.4*).

Why conduct a vulnerability assessment?

Having some understanding of vulnerability before beginning the asset management planning process is not required but can be beneficial to jump start discussions of resilience. At a basic level, a vulnerability assessment provides insights into the location, extent, and severity of environmental hazards that could damage transportation assets (through damage during extreme weather events and/or gradual deterioration due to climate change). More robust vulnerability assessments provide information on how roads and bridges may be impacted by changing environmental conditions and extreme weather and how disruptive those impacts may be to the network, and support identification of communities particularly vulnerable to the loss of transportation service caused by climate change or extreme weather.

Some transportation agencies or a partner agency may have already conducted a vulnerability assessment that can provide an understanding of environmental hazards and their potential impacts on the transportation network. If this is the case, *Section 3.4: How can vulnerability assessment outputs be used in asset management?* may be of more interest than other parts of this section.

If a vulnerability assessment has not been completed, review *Section 3.1* and *Section 3.2* on determining current and future environmental hazards. Next steps might include continuing with the vulnerability assessment (*Section 3.3*) to develop a more robust understanding of system vulnerability to natural hazards, or using the hazard information to jump to a risk assessment (*Chapter 7: Establish Risk Management Process*).

Traditionally, agencies have designed infrastructure for a specific range of environmental conditions and have based expectations for future environmental conditions on historical records and assumptions of stationarity (i.e., the idea that future patterns of weather and variability will match those of the past). It is important that agencies understand their vulnerabilities to both current, and future environmental conditions affected by climate change, to appropriately design and manage infrastructure, prepare the system for extreme weather events and associated service disruptions, and optimize operational planning efforts. Agencies should ultimately use their understanding of natural hazards and vulnerability to address risks from extreme weather events and climate change throughout the entire asset management process.

Understanding vulnerability may help an agency identify and address transportation system vulnerabilities.

Vulnerability Assessment vs. Risk Management

The vulnerability assessment has some similarities, and important differences, from the risk management process often included in an asset management plan. Both involve identifying potential hazards or threats and developing strategies to address them.

Vulnerability is a function of an asset's or system's exposure, sensitivity, and adaptive capacity to extreme weather events and climate change (FHWA, 2017f):

- **Exposure**: whether an asset or system is located in an area experiencing direct effects of current or future extreme weather. For example, an exposed road could experience inundation due to its location in a low-lying area.
- **Sensitivity**: how the asset or system fares when exposed to extreme weather or future environmental conditions. For example, a tunnel could be more sensitive to flooding due to the challenges of removing water.
- **Adaptive capacity**: the system's ability to cope with impacts of extreme weather or future environmental conditions. For example, alternative routes that could be used to reach the same location would increase adaptive capacity compared to a route that lacks redundancy.

Risk is the positive or negative effects of uncertainty or variability upon agency objectives (23 CFR 515.5). In the context of resilience, risk is often assessed as a product of the qualitative or quantitative **likelihood** that an asset will experience a particular stressor, and the **consequence** of that impact.

The vulnerability assessment can be a useful input for assessing the likelihood and consequences of environmental risks. Specifically, exposure data can inform the likelihood of impact while sensitivity and adaptive capacity data can help determine the severity of consequences. For example, an asset that is highly sensitive to flooding would experience more severe consequences than an asset that has flood-proofing measures in place. For more information on the risk management process, see *Chapter 7: Establish Risk Management Process*.

Vulnerability assessments can range in scope in terms of both the transportation assets (e.g., single projects, entire transportation networks) and key hazards or risks (e.g., flooding, extreme heat).

FHWA has developed a Vulnerability Assessment and Adaptation Framework that provides a detailed approach for agencies to consider in conducting a vulnerability assessment. Figure 3-1 depicts the framework for assessing vulnerability and adaptation strategies.

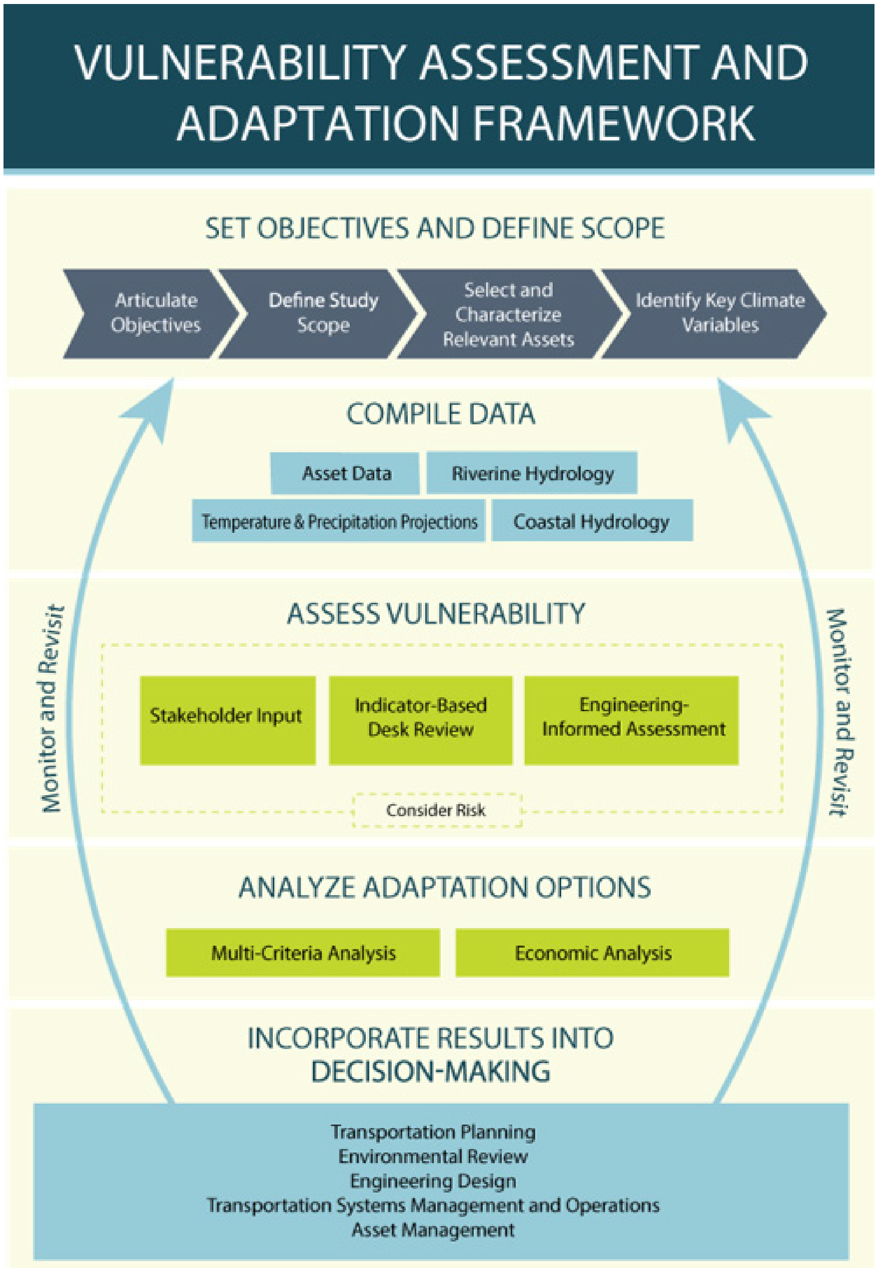

Figure 3-1: FHWA vulnerability assessment and adaptation framework conceptual diagram.

The information presented in the framework is intended for State DOTs, MPOs, and other agencies involved in planning, building, maintaining, or operating transportation infrastructure. The key steps included in the framework are:

Set objectives and define scope: Set the scale of the vulnerability assessment, including determining which natural hazards and assets to analyze. *Section 3.1: What are the relevant* *hazards?* provides an introduction on how to identify relevant hazards for asset management planning.

Compile data: Collect relevant asset data from both internal and external sources. Compile both current and future environmental hazard data for the relevant hazards. *Section 3.2: How are the hazards changing?* provides an introduction to potential data sources for understanding how current environmental conditions may be changing in the future.

Assess vulnerability: Evaluate the exposure, sensitivity, and adaptive capacity of each asset or the transportation system as a whole using one of three approaches: stakeholder input, indicator-based desk review, or engineering-informed assessment. These approaches are explained more fully in *Section 3.3: How resilient is the transportation system?*

Analyze adaptation options: Evaluate adaptation options using multi-criteria analyses and economic analyses. These methods allow practitioners to consider aspects that cannot be easily quantified, clarify potential long-term costs and benefits, and compare options both individually and with current policies.

Incorporate results into decision-making: Study results may be used in practice by incorporating assessment results into transportation planning; project development and environmental review; project level design and engineering; transportation systems management, operations, and emergency management; and asset management.

In addition to the Vulnerability Assessment and Adaptation Framework, FHWA has created a number of resources and tools for supporting vulnerability assessments, including:

- Transportation Climate Change Sensitivity Matrix: A tool on the sensitivity of various types of transporation assets to particular hazards. The hazards covered in the tool include increased temperature and extreme heat, precipitation-driven inland flooding, sea level rise/extreme high tides, storm surge, wind, drought, dust storms, wildfires, winter storms, changes in freeze/thaw cycles, and permafrost thaw (USDOT, 2014).
- CMIP Climate Data Processing Tool 2.1 : A tool designed to process readily-available downscaled climate projections data at the local level into relevant statistics for transportation planning (FHWA, 2020)
- Vulnerability Assessment Scoring Tool (VAST): A tool intended for agencies assessing how components of their transportation system are vulnerable to hazards. It helps especially with rating and ranking vulnerabilities for large numbers of assets. An asset manager can use VAST to catalog and sum up vulnerabilities for different asset categories and/or all assets addressed in a TAMP, and this information could be used in the TAMP to identify and rank extreme weather-related risks.The tool guides users through conducting a quantitative, indicator-based vulnerability screen (USDOT, 2015).
- Case Studies: The FHWA has supported the development of an extensive series of case studies on resilience in the transportation sector, including a pilot series on vulnerability assessments.
- Hydraulic Engineering Circulars (HEC) No. 17, 2nd Ed and No. 25, 3rd Ed.: These documents provide guidance for analysis, planning, design, and operations of highways in riverine (HEC 17) and coastal environments (HEC 25).

- TechBrief: Climate Change Adaptation for Pavements: An overview of temperature, precipitation, sea level rise, and pavement-specific impacts. It addresses specific pavement adaptation strategies that can be implemented now and in the future (FHWA, 2015c).

Using the USDOT Vulnerability Assessment Scoring Tool (VAST) in Asset Management

An indicator is a characteristic of an asset or its surroundings that can be used as a proxy measurement of the asset's vulnerability to a given stressor based on its exposure, sensitivity, or adaptive capacity (USDOT, 2015; FHWA, 2017f). VAST is a tool that can be used to conduct an indicator-based vulnerability assessment and includes a range of indicators for each component. As DOTs and MPOs have completed indicator-based vulnerability assessments, a number of best practices and recommendations for agencies working with indicators have emerged:

Selecting indicators:

- Avoid redundant metrics. Using more indicators may skew, and does not necessarily correlate with better, results. Consider using five or fewer indicators for each component.
- Use indicators that are easy to collect or derived from data already collected for other goals.
- Use an iterative process to balance desired indicators, data availability, and data collection requirements, and considering available resources. Limit the vulnerability assessment to assets and hazards with high quality data.
- Engage engineers, asset-owners, and other staff familiar with assets to help select and determine weights for relevant indicators to encourage acceptance of the vulnerability assessment results.
- For adaptive capacity indicators, aim to capture impacts to system users, for example annual average daily traffic, detour length, evacuation route designation, or duration of impact.

Scoring indicators:

- Consider screening out assets that will not be affected/exposed to a given stressor and only calculating vulnerability scores for exposed assets.
- Score each indicator's raw values on a common scale (e.g., 1-4). When assigning indicators to a common scale, consider the spatial extent of scoring and desired end use of the vulnerability assessment (e.g., score statewide or by district). Set scoring interpretation rubrics as a guide.
- Consider separating analyses based on asset owner or functional class (e.g., state vs. local).

Weighting indicators:

- Allow indicators to have different weights based on importance and confidence level and gather input on assigned weights. For example, assign past experience with the hazard a higher weight than other indicators.
- Conduct sensitivity tests for weighting schema to determine if altering weights produce significantly different vulnerability scores.

Ground-truthing:

- Incorporate some measure of past experience as an indicator (e.g., survey of maintenance staff).
- Seek out maintenance staff/asset owners to review draft results, perhaps through interactive maps. Consider asking: Does anything surprise you? Is anything not showing up as vulnerable that should? In addition, encourage vetting of results after an extreme weather event to determine the best-performing indicators.
- When designing resilient replacement projects using in-depth site-specific calculations vulnerabilities, compare results from the indicators to the actual level of vulnerability from the site-specific study. Adjust indicators or weightings based on lessons learned from the project-level analysis.

3.1 What are the relevant hazards?

Transportation systems can be vulnerable to a range of extreme weather events such as heat waves, heavy precipitation and flooding, extreme high tides, storm surge, wind, drought, and wildfires. Many of these will be exacerbated by climate change, though the exact changes will vary by region. Table 3-1 provides a summary of what is known regarding transportation asset sensitivities to a range of environmental conditions.

Table 3-1. Environmental Conditions That Could Affect Asset Condition, According to FHWA Sensitivity Matrix (Adapted from (FHWA, 2017d))

Asset	Extreme Temperature	Inland Flooding/ Precipitation	Sea Level Rise	Storm Surge	Wind	Drought	Changes in Freeze/ Thaw	Permafrost Thaw
Pavements	✓	✓	✓	✓	✕	✓	✓	✓
Bridges		✓	✓	✓	✓		✓	✓
Culverts		✓	✓	✓				
Slopes and Soils	✓	✓	✓	✓		✓		✓
Mechanical/ Electrical Equipment	✓	✓	✓	✓	✓			

*Checkmarks indicate a documented relationship between the asset type and the environmental condition, Xs indicate it is very unlikely there is a relationship between the asset type and environmental condition; blanks indicate little or no research on the topic.

As part of understanding current and future vulnerabilities, it may be useful to determine which extreme weather events have the greatest effects on the transportation network, both now and in the future. Understanding relevant vulnerabilities can assist agencies in developing risk-based goals that consider current and future environmental conditions and optimal best-cost approaches for managing risks to assets over their lifetime, as well as identifying assets that may need to be more closely monitored over time. When collecting information on hazards of concern, consider also collecting information on how these hazards have impacted specific assets or the system in the past. This information can help to complete the steps in *Section 3.3: How resilient is the transportation system?*

Historical performance and agency knowledge

Past system or asset performance during extreme weather events can indicate which hazards are most relevant to include in the vulnerability assessment. To identify assets vulnerable to current and future environmental conditions, consider the following sources of information.

- *Consult maintenance, operations, emergency management, and engineering records.* These may contain specific information on the characteristics of disruptive extreme weather events, such as temperature associated with pavement damage or total precipitation that flooded a road. For example, NJDOT worked with New Jersey's Bureau of Pavement & Drainage Management and Technology to obtain data from an existing drainage management system with details on flooding incidents and maintenance records (NJDOT, 2019).

- *Perform GIS hot spot analysis*. Consider developing a GIS database to collect information on damaging events (e.g., location, type of damage, cause of damage, cost of repair) to help visualize the types and locations of hazards causing damage. One benefit of inputting this information into GIS is that it also allows agencies to look beyond individual assets to identify repeated damage or broader trouble areas or "hot spots. For example, buffering damaged assets by a set distance (e.g., 500 feet) can identify hazards that intersect.

  When performing a GIS hot spot analysis, simultaneously collect information about assets that have been impacted in the past. For example, the "Blue Spot Model" used in Denmark, Switzerland, and the Netherlands is a geospatial methodology that identifies road segments where the likelihood of flooding is relatively high and where its consequences are significant. The Danish Road Directorate used the model to identify both existing vulnerabilities under current environmental conditions as well as new potential blue spots based on future environmental conditions (Climate ADAPT, 2010). Although each individual asset may only have been damaged once, multiple events over time imply a more systemic problem in the area.

- *Solicit expert opinion from maintenance and operations personnel, emergency managers, and engineers* about vulnerabilities of the systems and key assets they manage. Discuss which weather extremes are most impactful to services or assets, and whether there are thresholds at which the system begins to experience impacts (FHWA, 2011b). For example:

  - The Texas DOT (TxDOT) transportation asset management plan includes a detailed section on identifying risks from current environmental conditions (TxDOT, 2018). It lists as high-priority risks the occurrence of unanticipated weather events or natural disasters such as a hurricane resulting in system damage. The TAMP notes that Texas has 367 miles of coastal exposure on the Gulf of Mexico, which makes it more likely that these exposed roads will face hurricanes, tropical storm winds and surging Gulf waters. Also, droughts cause deterioration to highways because many Texas facilities are constructed on clay soils that expand and contract with changes in soil moisture content. The plan notes that Hurricane Harvey in 2017 produced the largest historical rainfall from a single event in the State's history and represents the type of predominant threat to Texas infrastructure. TxDOT reported that about 2 percent of the agency's bridges were vulnerable to 100- to 500-year flood events, and those were singled out for scour repair and other mitigation practices.

  - Caltrans District 1 overlaid projected changes in precipitation and sea levels with historical maintenance events in GIS (Caltrans, 2014). This analysis helped evaluate the potential for future impacts, defined as the level of interruption of service of the asset.

    - Using another tactic, the MDOT SHA asset management pilot team distributed a simple, map-based survey to district maintenance staff to capture information on past flooding issues at bridge assets (MDOT SHA, 2019).

- *Review assets identified under* 23 CFR Part 667. State DOTs are required to evaluate roads, highways, and bridges that have required repair and reconstruction activities on two or more occasions due to emergency events and to determine if there are reasonable alternatives.[1] An emergency event is defined as a natural disaster or catastrophic failure resulting in an emergency declared by the State Governor or President (23 CFR 667.3). Review data on repeatedly damaged facilities and extract information about the hazards causing those damages. Keep a record of which assets are vulnerable to a particular hazard. Data sources may include reports or associated information developed to receive emergency repair funds, data sources used to apply for Federal or nonfederal funding, and State or local records pertaining to damage sustained and funding needs. See FHWA's Questions and Answers Regarding Implementation of 23 CFR Part 667 for more information.

- *Review projects submitted to FHWA for Emergency Relief (ER) funding reimbursement*. The Emergency Relief Program helps to repair serious damage to Federal-aid highways resulting from natural disasters or catastrophic failures (see 23 U.S.C. 125; 23 CFR 668.101). Reviewing assets included in ER funding applications may help to identify hazards that have impacted the transportation system and involved significant funding to manage weather-related damage and deterioration. For example, the Post Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT mapped the geographic extent of projects submitted for ER Program reimbursements for Hurricane Sandy by asset class (see Figure 3-2) (FHWA, 2017c).

[1] Reasonable alternatives include options that could partially or fully achieve the following: reduce the need for Federal funds to be expended on emergency repairs or reconstruction; better protect public safety and health, and the human and natural environment; and meet transportation needs set out by Federal, State, local, and tribal plans and programs (e.g., long-range statewide transportation plans, statewide transportation improvement programs, metropolitan transportation plans, transportation improvement plans) (23 CFR 667.3).

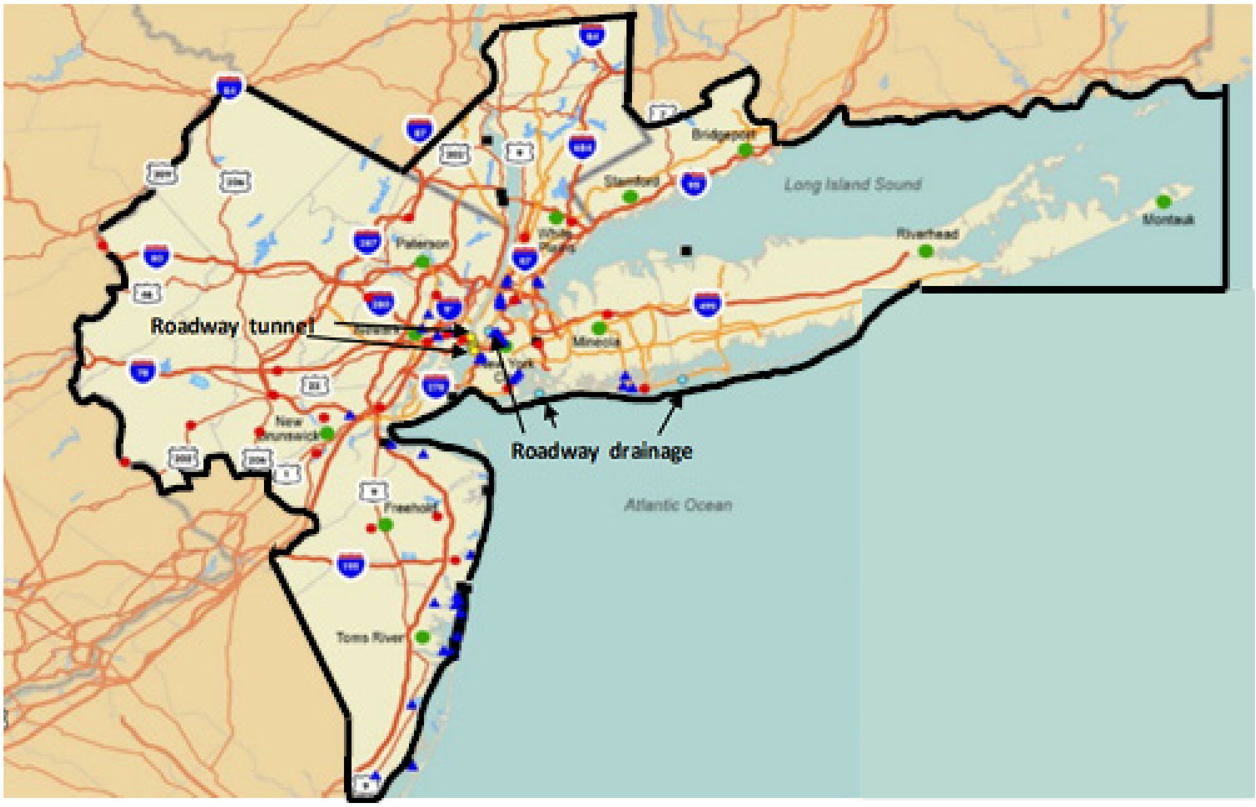

Figure 3-2. Projects submitted to FHWA for Emergency Relief funding reimbursement following Hurricane Sandy, by asset class, as of October 2013 (FHWA, 2017c).

Infrastructure design standards and guidelines

Reviewing the design standards and guidelines for different asset types is another way to determine the events that may be relevant over the service lives of particular assets. Such standards often provide values that indicate an asset's resilience to certain events, such as extreme temperatures or flooding. For example, Federal regulation specifies that Interstates comply with a design standard of not being overtopped by the 50-year (2% annual exceedance probability) flood event. (See 23 CFR part 650.115(a)(2). Other roads may have been designed to a smaller design flood. The next step is to understand how such events may change due to climate change.

3.2 How are the hazards changing?

Next, consider collecting data to understand how often relevant environmental hazards have occurred in the past and how they could change in the future as the climate changes.

What timeframes should be considered?

It is important to consider the full life-cycle of transportation assets when developing and implementing asset management plans, including required TAMPs. While the financial plan development process for a TAMP must identify the annual costs to implement the investment strategies in the TAMP over a minimum 10-year period (23 CFR 515.7(d)) (see *Chapter 9: Establish Resilient Investment Strategies and Financial Plans*), the life-cycle of bridge or pavement assets spans decades. This makes it important to have a strategic understanding of the asset class's life-cycle and the appropriate timing of interventions over the full life-cycle.

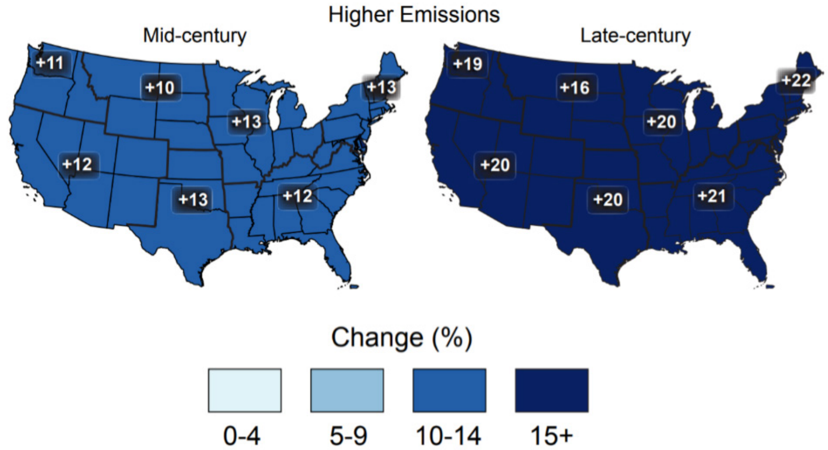

Figure 3-2. Projected changes in the 20-year return period amount for daily precipitation, shown for typical climate projection timeframes (e.g., mid- and late-century, RCP8.5 scenario, LOCA downscaled data) (Easterling, et al., 2017).

Significant changes in environmental conditions may occur over the life-cycle of an asset. Reports that summarize changes in environmental conditions and extreme weather (e.g., the National Climate Assessment) often describe projected future environmental conditions for future periods (e.g., 2030-2050, or 2070-2100) compared to today. For example, Figure 3-3 depicts projected future changes in rainfall intensity across the United States at mid-century and late-century timeframes (Easterling, et al., 2017).[2] Agencies should consider the relevant life-cycle for the asset classes. For example, assets with a design life of 30 years should consider climate change or extreme weather at mid-century, while assets with a longer design life, such as bridges, should consider extreme weather risks and climate change in the late century.

Some agencies have incorporated voluntary, longer-term performance targets into their asset management plans. For example, Pennsylvania DOT (PennDOT) includes performance targets for 10, 25, and 50 years in the future. The 50-year time horizon corresponds to expected pavement life (PennDOT, 2014).

What data resources are available?

The text box below provides a sample of resources for obtaining historical and future environmental condition data. For more information on these resources and how to apply them, see section 4.1 of FHWA's Synthesis of Approaches for Addressing Resilience in Project Development (FHWA, 2017d).

As noted in the text box, some State DOTs work with partners like universities, Federal agencies, or other State agencies to obtain data specific to their needs. For example, Iowa DOT partnered with Iowa State University to obtain data on projected continuous daily rainfall and with the University of Iowa Flood Center for hydrologic modeling that supported their vulnerability assessment (Iowa DOT, 2015). Similarly, NYSDOT partnered with the United States Geological

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[2] These projections illustrate potential future change at a regional level based on climate model data, but are not appropriate for use in design; the calculation approach may vary from standard approaches used in the transportation sector.

Survey (USGS) to develop an enhanced StreamStats tool that incorporated future environmental condition projections into streamflow statistics (NYSDOT, 2015).

Common Data Sources for Understanding Historical and Future Environmental Conditions

Historical	Future
• National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Information • NOAA's Precipitation Frequency Data Server (Atlas 14) • State Climatologist • University Climate Research Centers • State and Local Agencies Source: (FHWA, 2017f)	• U.S. Global Change Research Program's National Climate Assessment • FHWA's CMIP Climate Data Processing Tool • Global and Regional Sea Level Rise Scenarios for the United States • U.S. Army Corps of Engineers' Sea Level Change Curve Calculator • U.S. Geological Survey's National Climate Change Viewer • State Climatologists • University Climate Research Centers • State and Local Agencies

3.3 How Resilient is the Transportation System?

To understand the resilience of the transportation network (i.e., the potential impact of damage, accelerated deterioration, and/or service disruption in terms of impacts on cost, network performance, and natural environment), consider using the information gathered on relevant risks from current and future environmental conditions, along with other information, to conduct a vulnerability assessment. FHWA's Vulnerability Assessment and Adaptation Framework (FHWA, 2017f) describes three approaches to consider:

- **Stakeholder input approach**: Primarily used for systems-level or area analyses, this approach relies on institutional knowledge to identify and rate potential vulnerabilities. The stakeholder input approach incorporates knowledge and experiences from local communities and/or public agency staff to assess the transportation assets' or system's sensitivity to environmental conditions. The stakeholder input approach is informative for asset management because it is likely to identify vulnerable assets or types of assets that are critical to the overall system. For example:
    - Oregon DOT (ODOT) presented district maintenance crews and technical staff with a web-based GIS map with data on existing asset conditions, locations of known hazards and weather-related incident response, and future sea level. ODOT also mapped maintenance record location related to flooding, high water, landslides, and rockfalls. Using the historical and future hazard data and their

local knowledge, staff identified "climate hazard sites" on the map at a workshop (Oregon DOT, 2016).

- Washington State DOT (WSDOT) facilitated 14 workshops across the state to capture local knowledge and assess vulnerability. Participants used an asset inventory, maps of asset locations, and historic and projected hazard impact maps for sea level rise, temperature, precipitation, wind, and fire from the University of Washington for the assessment. Participants ultimately rated asset criticality and the impact of future environmental conditions on WSDOT infrastructure on a qualitative scale (FHWA, 2014a).

- **Indicator-based desktop review approach**: Primarily used for systems-level or area analyses, this approach provides a low-cost way to score and rank transportation assets for vulnerability by relying on available data. By following this approach, agencies can use quantitative data on assets and future environmental condition data to serve as proxy indicators to evaluate potential vulnerabilities. The indicator-based desktop review approach is informative for asset management because it offers a big-picture understanding of system-wide vulnerabilities and may allow an agency to identify subsets of assets that warrant specific management strategies. For example, an agency may develop a different life-cycle planning strategy for roads that score as highly vulnerable to future environmental conditions and are currently in poor condition than for highly vulnerable roads that are currently in good condition.

Proxy Indicators

An indicator is a representative data element that can be used as a proxy measurement of the overall exposure, sensitivity, or adaptive capacity of a specific asset (FHWA, 2017f; FHWA, 2015c). Examples of indicators commonly used include:

- Inundation depth under future sea level rise scenarios
- Average annual daily traffic
- Rutting of asphalt surface

- **Engineering-informed assessment**: Focusing on a specific transportation asset, this approach is characterized by a high level of asset-specific data and analysis. This approach offers a way to evaluate how changing environmental conditions are affecting a particular asset. Engineering-informed assessments may be more appropriate as a secondary assessment once an agency has conducted a stakeholder or indicator-based desktop assessment. This approach is also useful during initiation of a planning study to assess future environmental conditions and the effectiveness of a specific adaptation measure. These types of assessments do not address the entire transportation system and thus will not be as informative for asset management planning except for unique or high-cost assets.

For example, aging, high-cost bridges may warrant an engineering-informed assessment as part of a long-term asset management strategy. If high-cost structures or pavement sections are deemed vulnerable, an engineering-informed approach may be appropriate for these sub-categories of assets. This information could also inform group/sub-category analyses. Agencies may choose to conduct an engineering-informed assessment at the corridor or network scale (also known as subareas). For example, a Post Hurricane Sandy Transportation Resilience Study in New York, New Jersey, and Connecticut identified vulnerable subareas based on their relative concentration of critical infrastructure and a qualitative assessment of vulnerability. The project team then performed engineering-informed vulnerability assessments for several of these study areas with the aim of developing adaptation strategies for transportation assets (see Figure 3-4) (FHWA, 2017c).

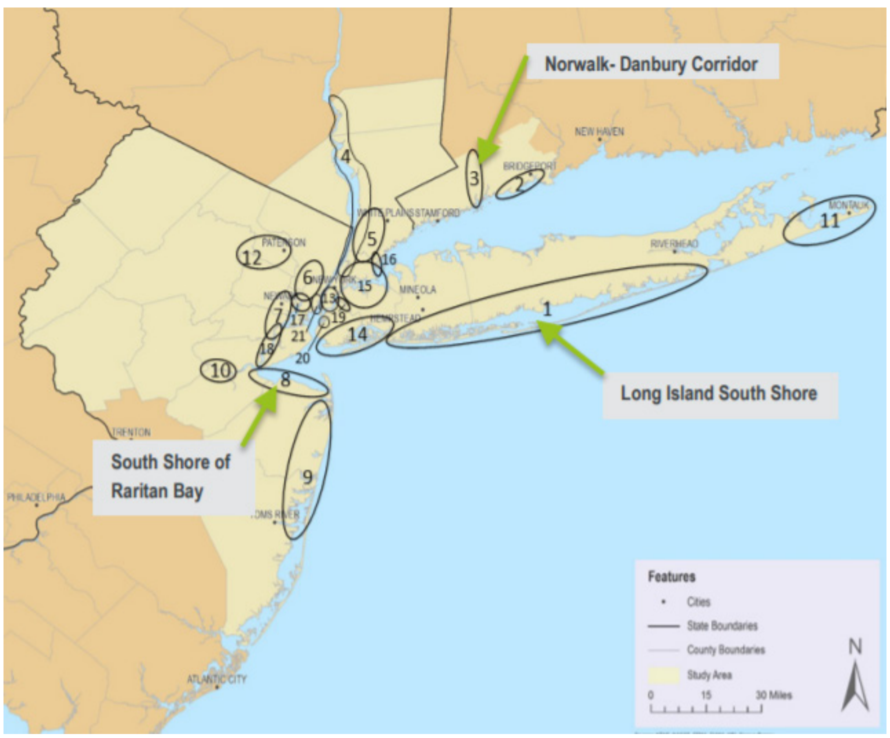

Figure 3-3. Subareas included in Post Hurricane Sandy Transportation Resilience Study engineering-level assessments (FHWA, 2017c).

There are many examples available that use each of the approaches described above:

- U.S. DOT Gulf Coast Study, Phase 2 for agency examples and other tools and resources for conducting vulnerability assessments (FHWA, 2014b).
- FHWA 2010-2011 Climate Change Resilience Pilots for examples (FHWA, 2011a).
- FHWA 2013-2015 Climate Change Resilience Pilots for examples (FHWA, 2016a).
- Synthesis of Approaches for Addressing Resilience in Project Development (FHWA, 2017d)

The FHWA-funded asset management pilots used a variety of approaches for their vulnerability assessments (see Table 3-2).

Table 3-2. Approaches for Vulnerability Assessments Used in the FHWA-Funded Asset Management Pilots

Pilot	Stakeholder -input*	Proxy Indicator -based	Engineering-informed	Details
ADOT		✓		ADOT used an intersection analysis of the roadway system to identify proxy indicators including: previous incidents, functional classification, and temperature change by 2050.
KYTC		✓		KYTC used National Bridge Inventory data to develop flood and scour risk indicators.
MassDOT		✓		MassDOT used proxy variables that are now easily estimated at the state scale to perform an initial flood resilience screen for bridges and culverts.
MDOT SHA		✓		MDOT SHA completed an indicator-based assessment of vulnerabilities from sea level rise, storm surge, and inland flooding hazards.
NJDOT		✓		The NJDOT approach involved intensive data collection, analysis of data, and GIS intersection analysis to assess the impacts to roadways at the selected case study areas.
TxDOT			✓	TxDOT conducted a simulation study to assess the performance of water inundated flexible pavements in TxDOT's Houston District given different scenarios of traffic levels, pavement structures, and flooding events
*** While many vulnerability assessments used the proxy-indicators approach, most of the pilots incorporated a robust stakeholder engagement component as well**.				

3.4 How can vulnerability assessment outputs be used in asset management?

There are several ways to use a vulnerability assessment to inform asset management. Not all hazards, such as storm surge, are applicable to all assets within a particular asset class or subgroup.

Vulnerability assessments are typically conducted according to the stressor being evaluated, such as flooding due to precipitation in a specified location. Traditional groupings of assets for asset management and life-cycle planning purposes occur at the network level (e.g., NHS, Interstates, State routes), and for groups or sub-groups of similar assets. Examples include jointed concrete pavement as a subgroup of pavement assets on the Interstate system, or truss bridges as a subgroup of bridge assets on the NHS. These groupings allow agencies to determine strategies and costs for managing these groups or subgroups over their lifetimes, including setting targets for asset condition and identifying deterioration models.

Existing assessments may include a range of networks or asset classes without clear distinction. Some systems-level vulnerability assessments have focused more on counties or districts and less on specific networks such as the NHS, and then limited the focus according to asset/corridor criticality, which each State or MPO may define differently. For example, Minnesota DOT performed a system-level screening to determine vulnerability to precipitation change state-wide, and the Metropolitan Transportation Commission (California) assessed vulnerability of the Alameda County transportation system to sea level rise. States have also examined vulnerabilities for specific locations or projects, such as an individual bridge, embankment or section of a highway. In terms of assets, they could focus on specific asset groups (e.g., bridges) and/or roadway networks (e.g., NHS and non-NHS).

Risks identified in existing vulnerability assessments may only affect part of the network or parts of existing groups or sub-groups of assets. However, States can often use the results of broader systems level assessments to catalog results by groups or sub-groups. States can also draw information from other sources, including more detailed asset or project level assessments and broad systems-level information to support asset class or subgroup analyses.

4 DEVELOP ASSET INVENTORY

This chapter and all following chapters pertain directly to integrating consideration of extreme weather events and climate change into transportation asset management plans and processes. Yellow textboxes are intended to provide a snapshot of key entry points and opportunities for considering extreme weather events and climate change in the federally required TAMP.

Typically, the first step in preparing an asset management plan is to develop an asset inventory and associated asset condition information. The inventory is an opportunity to identify groups of assets that are vulnerable to extreme weather events and changing environmental conditions due to their location, sensitivity to the hazard, and their adaptive capacity and criticality to the function of the network. Grouping and acknowledging vulnerable assets in the asset inventory allows their unique considerations to be carried through the entire asset management plan.

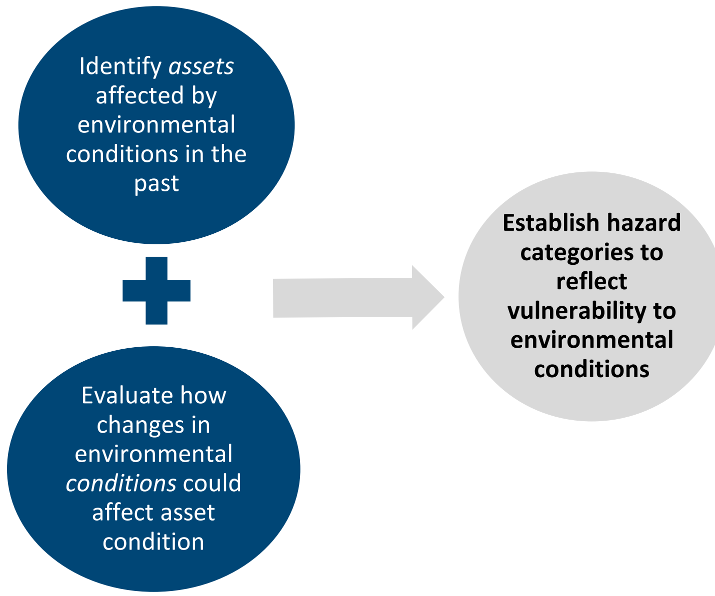

Figure 4-1. Overview of integrating resilience into the asset inventory.

To integrate vulnerability data into the asset inventory and asset condition, agencies can build on the vulnerability assessment information to determine which (if any) vulnerable assets should be grouped for independent evaluation (see *Chapter 3: Understand Vulnerability to Extreme Weather Events and Climate Change* for more information on identifying vulnerable assets). See Figure 4-1.

The traditional group of assets at the asset class or asset sub-group level within networks allows agencies to determine strategies and costs for managing these groups over their life. Agencies can use common characteristics of these groupings to develop and leverage deterioration models, manage potential work types based on unit cost, and develop a strategy for managing the grouping by minimizing life-cycle costs while achieving asset condition targets (FHWA, 2013a).

In addition, the asset condition data gathered during this step provides context for the asset management planning process. For example, asset condition serves as the basis for the gap analysis between existing and target condition levels (*Chapter 5: Conduct Performance Gap Assessment*), informs the development of objectives and targets (*Chapter 6: Set Resilience Objectives, Measures and Targets*), and can be used to track the progress and effectiveness of life-cycle strategies through time (*Chapter 8: Develop Life-cycle Plan*).

4.1 Establish Hazard Categories to Reflect Vulnerability to Environmental Conditions

Threats to infrastructure can increase long-term life-cycle costs or influence life-cycle strategies. Certain assets assumed to have predictable service lives could perform differently in the future if, for example, temperatures are significantly warmer or the asset experiences more frequent flooding than expected. Weather events could increase unit costs due to high demand or decrease in service life. Using the asset inventory to capture assets whose future performance may differ from past performance can inform life-cycle or investment strategy decisions.

> **Condition data reflects historical deterioration and damage**
>
> Asset condition data reflect past damage and deterioration. For example:
>
> Rain, flooding, tidal issues, overtopping, and inadequate culverts can
>
> - Cause deterioration: the frequency and duration of inundation impacts pavements
> - Cause damage such as washouts
>
> Temperature can
>
> - Cause deterioration: rutting or oxidation (faster aging which can lead to cracking and raveling, etc.)
> - Cause damage: such as blow ups with concrete in extreme heat

Vulnerable assets that are damaged more frequently in the future will have increased costs (due to higher repair needs). These assets may be associated with more frequent inspection, cleaning, or maintenance to reduce vulnerability, which are considerations in the financial plan (see *Chapter 7: Establish Risk Management Process* for more information on understanding and mitigating extreme weather damage risks). By flagging these types of assets in the inventory, agencies can better anticipate the need for, and magnitude of, future treatments (see *Chapter 8: Develop Life-cycle Plan* for more information on how to address gradual changes in deterioration). Because almost all planning analysis begins with the attributes captured in the asset inventory, incorporating vulnerability information into the inventory allows the agency to plan more effectively.

Transportation agencies can use the results of a vulnerability assessment to further categorize classes or subgroups of assets based on particular hazards or stressors (extreme temperature risks, flood risk, etc.). One advantage of further categorizing assets into hazard categories is the ability to develop appropriate asset management strategies for multiple assets (and in some cases across asset classes) rather than individually, such as timber bridges exposed to flooding. When determining hazard categories, consider the environmental hazards that:

- Have the potential to result in catastrophic damages to assets during extreme weather events. For example, storm surge in combination with other factors, such as sea level rise or other climate change effects, has the potential to damage low lying infrastructure, including bridges, in coastal areas. Sea level rise can facilitate increased damage and/or cause storm surge to reach further inland, potentially impacting more assets.
- Are more likely to result in slow but notable increases in asset deterioration due to gradual changes in temperature, precipitation, sea level rise, and other environmental conditions.

- Reduce system performance (either temporarily or permanently) or increase user costs.
- Reduce the likelihood of target achievement.

Once assets are identified as highly vulnerable to a condition of concern, they can be grouped together in the asset inventory. For example, the following hazard categories might emerge from the vulnerability assessment or other agency efforts:

- High sea level rise vulnerability: Pavements and bridges located in future inundation areas.
- High drought and heavy precipitation vulnerability: Pavements constructed on expansive soils that are sensitive to fluctuations in drought and heavy precipitation.
- High inland flooding vulnerability: Bridges and approaches in areas where the bridge hydraulic opening affects flood elevation (*i.e.*, the backwater potential is high) and/or where flood discharges are expected to increase because of increased precipitation. (Reflects both impacts to structures and resulting system/mobility impacts.)
- High vulnerability to unstable slopes: Assets located near slopes deforested by fires or made unstable by soil saturations (which could be caused by rainfall).
- High vulnerability to frequent and intense storms: Aging culverts subject to loss of performance due to deterioration and exacerbated by potential heavy inundation.
- High wind load vulnerability: Aging overhead signs or high mast lighting could be subject to increased wind loads and frequency and may be singled out for resilience activities.

Consider the entire life-cycle of assets, including impacts from future environmental conditions that may not come to pass until after the sunset date of the current asset management planning process.

Consider including in the TAMP Asset Inventory: Hazard categories to reflect vulnerability to environmental conditions

Break out categories of vulnerable assets into your inventory and asset condition reporting. Table 4-2 depicts a simplified summary table that includes example hazard categories for the highest priority vulnerabilities. These hazard categories could combine asset categories with the hazard(s) most concerning to an agency (i.e., most likely to result in catastrophic damages or increases in asset deterioration).

Table 4-1. Example Inventory and Condition Summary Table with "Hazard Category" Column (outlined in red) Added to Capture New Categories of Assets at Risk from Extreme Weather or Changing Environmental Conditions

Asset Class	Asset Sub-Group	Hazard Category	Inventory			Asset Condition		
			Units	Quantity	Lane Miles or Square Meters	% Good	% Fair	% Poor
Pavements	Asphalt	High inland flood vulnerability						
		High sea level rise vulnerability						
	Concrete	High inland flood vulnerability						
		High sea level rise vulnerability						
Bridges	Moveable	High inland flood vulnerability						
	Timber	High sea level rise vulnerability						

4.2 Recap of Integrating Resilience into the Asset Inventory and Condition Reporting

As discussed above, the asset inventory is an opportunity to identify assets that are vulnerable to extreme weather events and climate change so their unique considerations can be incorporated through the various subsequent transportation asset management processes and analyses. Table 4-3 can be used to check off actions an agency has already taken to integrate resilience to extreme weather events and climate change into their transportation asset management process and prioritize remaining actions.

Table 4-2. Checklist of Potential Actions on Integrating Resilience Into the Asset Inventoryfor Transportation Asset Management

Complete?	What to analyze?	What to include?
	Determine if any of the identified vulnerabilities justify establishing a unique asset category based on historical experiences with extreme weather events or vulnerabilities to future environmental conditions/climate change.	If an agency does decide to identify new categories of vulnerable assets, consider integrating the hazard categories into asset inventory and condition reporting. Table 4-2 depicts a simplified summary table that includes example categories for the highest priority vulnerabilities.

5 Conduct Performance Gap Assessment

In general, a performance gap analysis assesses whether current and future asset condition and performance will meet the agency's objectives. An agency can examine its current conditions against its targets and review modeled predictions of future asset conditions to assess if these will be acceptable.

The performance gap analysis can assist agencies in developing risk mitigation strategies for extreme weather events (including associated investment strategies) and life-cycle strategies for future environmental conditions (see *Chapter 7: Establish Risk Management Process* and *Chapter 8: Develop Life-cycle Plan*, respectively). For example, if an agency finds that certain inundated pavements contribute disproportionately to the pavement performance gap, it may decide to alter pavement designs or increase maintenance funding. The information from a gap analysis is used in life-cycle planning (*Chapter 8: Develop Life-cycle Plan*) and financial planning (*Chapter 9: Establish Resilient Investment Strategies and Financial Plans*) to develop alternative strategies to address the identified gaps.

5.1 Determine if observed performance gaps are due to environmental conditions

As an agency identifies gaps in asset condition, it may be useful to assess whether any gaps are due to weather-related deterioration or damages, especially if other causes for the discrepancies in performance have been ruled out. For example, pavements on expansive soils may have larger performance gaps due to the challenges of managing the expansion and contraction of the soil during periods of heavy rainfall followed by dry weather. To determine if observed performance gaps are due to weather-related damages, consider following the steps outlined below, starting by identifying the lowest performing assets that are lowering the overall performance of the system. While the steps are not required under FHWA regulations, agencies can determine if there may be a weather-related cause for the low performance by:

- Engaging knowledgeable staff,
- Leveraging vulnerability assessment results (*Chapter 3: Understand Vulnerability to Extreme Weather Events and Climate Change*), or
- Comparing to the vulnerability categories created as part of the asset inventory (*Chapter 4: Develop Asset Inventory*).

Engage knowledgeable staff. Further explore performance gap data and results with the help of staff familiar with the asset to identify gaps related to current or future environmental conditions. Consider presentation of the performance gap data to maintenance staff by displaying the locations and other characteristics of the assets that are not meeting performance goals. Consider asking such questions as:

- Have any of these assets experienced damage or disruption from extreme weather events?
- Is it likely that the performance gaps are due to gradual deterioration accelerated by changes in environmental conditions such as temperature or nuisance flooding?

Leverage vulnerability assessment results. Agencies may also wish to compare the low performing assets or asset categories to the vulnerability assessment findings (see *Chapter 3: Understand Vulnerability to Extreme Weather Events and Climate Change* for a discussion of vulnerability assessments). An agency may have engaged knowledgeable staff as part of the vulnerability assessment process (e.g., to identify locations that have experienced damage or disruption from weather-related events), so reviewing the vulnerability assessment results may help determine if performance gaps are due to environmental conditions. Graphic representations of the relationship between performance gaps and associated vulnerability data can help determine if environmental conditions are a factor in performance gaps. For example, if a significant number of the low-performing assets have high vulnerability scores, this may be an indication that the performance gaps are due to environmental conditions.

Compare to vulnerability categories created as part of the asset inventory. Agencies may leverage the outcomes of the asset inventory (*Chapter 4: Develop Asset Inventory*) as another way to determine if asset condition and performance gaps are due to natural hazards. If an agency chose to develop asset hazard categories to reflect vulnerability to environmental conditions, it may have already determined the categories and hazard combinations that:

- Are most likely to result in catastrophic disruptions or damages during extreme weather events.
- Are more likely to result in slow but notable increases in asset deterioration.
- Reduce system performance (either temporarily or permanently) or increase user costs.
- Reduce the likelihood of target achievement.

Consider including in the TAMP Performance Gap Assessment: Determine if observed performance gaps are due to environmental conditions

Performance gap means the gaps between the current asset condition and State DOT targets for asset condition, and the gaps in system performance effectiveness that are best addressed by improving the physical assets (23 CFR 515.5). If an agency analysis indicates that environmental conditions may contribute to difficulties in meeting performance targets, consider including a description of these findings in the performance gap write-up.

5.2 Recap of Integrating Resilience into the Performance Gap Assessment

The performance gap assessment is an opportunity to determine if observed performance gaps are due to environmental conditions and identify which performance measures will be most affected by changes in environmental conditions. Table 5-1, can be used to check off actions an agency has already taken to integrate resilience to extreme weather events and climate change into the transportation asset management process and prioritize remaining actions.

Table 5-1. Checklist of Potential Actions on Integrating Resilience Into the Performance Gap Assessment for Transportation Asset Management

Complete?	What to analyze?	What to include?
	Determine if observed performance gaps are due to environmental conditions by: • Engaging knowledgeable staff to determine if low-performing assets have experienced disruption or damage from extreme weather conditions in the past. • Leveraging vulnerability assessment results to determine if there is a relationship between low-performing assets and high vulnerability scores. • Comparing low-performing assets to the asset / hazard categories created as part of the asset inventory.	If an agency's analysis of performance gaps indicates that environmental conditions may contribute to difficulties in meeting its goals, include a description of the findings in the performance gap write-up.

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6 Set Resilience Objectives, Measures and Targets

Extreme weather events and climate change represent a risk to transportation assets that can impact conditions impeding achievement of transportation objectives, measures, and targets, whether they are in the long-range plan, the TAMP, or in agency business plans. For example, more frequent extreme heat events could affect state of good repair objectives by accelerating the deterioration of assets and increasing the need for maintenance. Transportation agencies can more effectively achieve management objectives and targets when they take steps to manage extreme weather events and climate change risks. Defining agency objectives to address risks to extreme weather and future environmental conditions can be important for setting the strategic direction of the transportation asset management plan and influencing other components of the asset management process.

By way of example, one resilience objective could be that the agency desires no increase in the lane miles of roadway at risk of sea level rise. Or the agency could reduce the number of slopes at risk of failure because of fire and flood threat. Another resilience objective could be to improve outfalls that are likely to be submerged by higher river or sea levels.

Resilience measures and targets are important for measuring progress toward increasing resilience and for making informed investment and management decisions. Agencies can integrate resilience considerations into existing measures and targets or develop stand-alone resilience measures and targets that track strategies that are intended to mitigate the impact of specific extreme weather risks by making the system more resilient. While these approaches are not required under FHWA regulations, they can facilitate measuring progress and making decisions.

6.1 Modify Existing Objectives, Measures and Targets to Address Resilience to Extreme Weather Events and Climate Change

Use knowledge of environmental hazards from *Chapter 3: Understand Vulnerability to Extreme Weather Events and Climate Change* and the results of the gap assessment in *Chapter 5: Conduct Performance Gap Assessment* to determine an agency's ability to achieve existing objectives, measures and targets. Agencies can consider the following questions modified from FHWA’s *Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance* (FHWA, 2015a) when evaluating objectives, measures and targets in the context of extreme weather events and climate change:

- Do extreme weather events and climate change have direct effects on meeting agency objectives, measures and targets?
- Do extreme weather events and climate change affect the underlying assumptions upon which agency objectives, measures and targets are founded?
- To what extent are environmental conditions likely to change during the time horizon of the agency’s existing objectives, measures and targets?

Approaches for evaluating existing objectives, measures and targets based on environmental condition data and the results of the gap assessment include:

- Hold an internal meeting with personnel involved in asset management and environmental planning and resilience to determine if the agency's existing objectives, measures and targets can be achieved with consideration of extreme weather events and climate change.
- Hold similar meetings with external stakeholders to gather information for evaluating if existing objectives, measures and targets are feasible or appropriate.

Modify objectives

If an agency finds that existing objectives are infeasible or inappropriate given future environmental conditions, consider gathering input from internal and external stakeholders to modify existing objectives to better reflect changes in natural hazards. A few illustrative examples include:

- A transportation agency may have objectives related to system preservation and performance. However, gradual changes in environmental conditions like temperature and flooding can increase deterioration rates. As a result, the agency could modify current objectives to explicitly address future environmental condition considerations (e.g., strategically preserve, repair, or replace assets based on environmental condition projections over the lifespan of the asset).
- If an agency has an objective related to funding priority projects that improve infrastructure condition, consider modifying objectives to support climate change-informed design or project prioritization based on vulnerability to climate change.
- If an agency has objectives related to stormwater management, consider modifying the objectives to account for projected future precipitation (e.g., improve stormwater management to meet future projected precipitation levels by increasing the capacity of stormwater infrastructure or conducting more frequent maintenance).

Modify measures and targets

If an agency finds that existing measures and targets are infeasible or inappropriate given modifications to existing objectives or changes in natural hazards, consider gathering input from stakeholders to modify the language to better reflect expected changes in natural hazards and agency objectives. For example, an agency could modify targets related to the percentage of assets in good (or poor) condition to acknowledge that it may be harder to maintain assets in the future due to the impacts of climate change. The FHWA Sensitivity Matrix (USDOT, 2014) can be used to identify how asset condition may be affected by extreme weather events and climate change. Table 6-1 provides examples of extreme weather conditions, and the possible effects on assets, that might prompt an agency to reconsider its measures and targets.

Table 6-1. Illustrative Combinations of Asset Types and Extreme Weather and Climate Change Effects that May Pose the Greatest Risk to the Transportation System (FHWA 2017d, in part)

Extreme Weather	Impact to Asset	Effect on SOGR Targets
Sustained high temperatures	Asphalt concrete pavement may soften, resulting in rutting and shoving	Decreased ability to meet pavement index or asset condition target
Increased frequency of precipitation-driven inland flooding	Structural damage to culvert or conduit	Decreased ability to meet targets for culvert asset condition score
Sea level rise and extreme high tides	Increased erosion of roads and bridge approaches due to higher storm surges	Decreased ability to meet asset condition targets

6.2 Develop New Objectives, Measures and Targets to Address Resilience to Environmental Conditions

Modifications to existing objectives, measures and targets may not be sufficient to address new resilience challenges. If an agency has identified extreme weather events and climate change risk as a priority, establishing new resilience-related objectives, measures or targets can help demonstrate their importance internally and to the public. Also, if an agency has established specific resilience-related objectives, measures or targets, they could serve as the basis for directly addressing these as investment strategies in an asset management plan. Examples include targets for bridge condition as well as measures and targets focused on bridges potentially vulnerable to future sea level rise, where both situations are addressed in an asset management plan's investment strategy.

New objectives

It may be beneficial to work with stakeholders to develop new or additional resilience-related objectives that better meet the needs of an agency. Consider holding a work session dedicated to developing new objectives to increase resilience to extreme weather events and climate change. For example, a new objective could be identifying and increasing the resilience of critical assets where alternate routes are not an option. This could help improve the resilience of the transportation system and directly influence investment and management decisions.

Developing "SMART" objectives is an increasingly common best practice in performance-based planning and programming (FHWA, 2013b). The textbox at the right details the qualities of "SMART" objectives.

> **"SMART" Objectives**
>
> **Specific** – The objective provides sufficient specificity to guide formulation of viable approaches to achieving the objective without dictating the approach.
>
> **Measurable** – The objective facilitates quantitative evaluation, saying how many or how much should be accomplished.
>
> **Agreed** – Planners, operators, and relevant planning participants come to a consensus on a common objective.
>
> **Realistic** – The objective can reasonably be accomplished within the limitations of resources and other demands.
>
> **Time-bound** – The objective identifies a timeframe within which it will be achieved.

See Table 6-2 for examples of integrating resilience into transportation objectives. Although the majority of these examples are pulled from long range transportation plans (LRTPs), they are related to asset management and may help articulate asset management objectives. In addition, aligning objectives across multiple planning documents can be advantageous for facilitating a more comprehensive understanding and commitment to core objectives. In addition to those cited below, one could include objectives focused on reducing risks to disadvantaged communities.

Table 6-2. Examples of Integrating Resilience into Transportation Objectives

Goal	Objective	Plan
Vermont Agency of Transportation: Develop factual, risk-based, and data driven asset management processes to manage assets through their whole life **(VTrans, 2014)**	Develop a risk integration plan that formally considers and identifies risk and performance criteria in investment decisions (VTrans, 2014). *VTrans' strategies for achieving this objective specify that risks include those "associated with providing continuity of the service in relation to physical assets and system resilience such as hazard risks, extreme events, and physical failures."*	TAMP
Arkansas DOT: Provide a Safe and Efficient Intermodal Transportation System **(Arkansas DOT, 2018)**	Identify roadways and bridges that are vulnerable to extreme weather events and other natural phenomena (Arkansas DOT, 2018). Improve the resilience of the transportation system to meet travel needs in response to extreme weather events (Arkansas DOT, 2018).	TAMP
Minnesota DOT: System stewardship **(MnDOT, 2017)**	Strategically build, manage, maintain, and operate all transportation assets…. Increase the resilience of the transportation system and adapt to changing needs (MnDOT, 2017). *MnDOT defines system resilience as "reducing vulnerability and ensuring redundancy and reliability to meet essential travel needs. The transportation system is vulnerable to many types of threats and risks, such as severe weather.… Advanced preparation, mitigation and adaptation to threats and risks helps to ensure people and goods are able to continue to travel during emergencies."*	LRTP
Northeast Ohio Areawide Coordinating Agency: Build a sustainable multimodal transportation system **(NOACA, 2017a; NOACA, 2017b; NOACA, 2015)**.	Consider strategic abandonment or alternative provision of service for infrastructure elements that are underutilized or whose maintenance or reconstruction costs may exceed their benefit (NOACA, 2017a; NOACA, 2017b; NOACA, 2015). *NOACA includes this objective in the LRTP, Strategic Plan, and Water Quality Strategic Plan, highlighting the importance of consistency across planning documents.*	LRTP, Strategic Plan, Water Quality Strategic Plan
Palm Beach MPO (FL): Provide an efficient and reliable vehicular transportation system **(Palm Beach MPO, 2014)**.	Increase the percentage of facilities that can accommodate a two-foot sea level rise.	LRTP

Goal	Objective	Plan
Regional Planning Commission (LA): The transportation system we create today should positively impact the cultural fabric of our communities, and should be both financially and environmentally sustainable for future generations **(Regional Planning Commission, 2019)**	Increase the capability of the transportation system to continue functioning in the face of both periodic and chronic shocks and stressors	LRTP

New measures and targets

For particularly vulnerable asset types, transportation agencies may wish to develop new or additional measures and targets. In addition, agencies may wish to develop new measures and targets to support modified or new objectives related to extreme weather events and climate change.

Although resilience is generally considered on a long-term horizon, agencies can develop a series of short-term intermediate measures and targets to help achieve longer-term resilience objectives. Potential examples include:

- Increase lifespan of assets by X percent by implementing resilience strategies (e.g., making modifications to existing assets or replacing assets with more resilient alternatives).
- Increase percentage of usable bridges under X storm conditions (i.e., increasing the resilience of bridges to storm conditions).
- Decrease the hours of roadway lane miles closed due to flooding or other weather conditions by X percent.
- Decrease the number of roadway closures due to flooding or other weather conditions.
- Increase the percentage of culverts able to handle current and future channel discharge.
- Decrease percentage of facilities that are highly vulnerable to future environmental conditions, as determined by an indicator-based vulnerability assessment.
- Increase frequency of culvert cleaning at flood-prone locations.

Agency examples of resilience-related measures or targets are shown in Table 6-3. Although these examples are pulled from LRTPs, they are related to asset management and may articulate asset management measures and targets.

Table 6-3. Examples of Resilience-Related Objectives, Measures, and Targets

DOT or MPO	Goal or Objective	Measures or Targets	Plan
District DOT (District DOT, 2014)	Sustainability and health: Prepare the transportation system for changing environmental and climatological conditions.	Mileage of new facilities in flood zones (transit investments, bicycle facilities, streets, and bridges).	LRTP
Miami-Dade TPO (FL) (Miami-Dade TPO, 2014)	Reduce the vulnerability and increase the resilience of critical infrastructure to the impacts of climate trends and events.	Number of highway lane and centerline miles within the 100-year floodplain.	LRTP
Palm Beach MPO (FL) (Palm Beach MPO, 2014)	Provide an efficient and reliable vehicular transportation system.	Increase the percentage of facilities that accommodate two feet sea level rise; the performance target is 90% for the strategic intermodal system network in 2025.	LRTP

Consider including Objectives and Targets in the TAMP: Specific objectives, measures and targets to address risks from extreme weather events and climate change.

Consider modifying existing objectives, measures and targets if they are likely to become infeasible under future environmental conditions. In addition, if existing objectives, measures and targets do not adequately measure or account for climate change, consider developing new resilience-related targets for vulnerable assets to better measure progress toward increasing your resilience.

6.3 Recap of Integrating Resilience into Objectives, Measures and Targets

Establishing new -- or modifying existing -- objectives, measures and targets provides an opportunity for managing risk from current and future environmental conditions and addressing resilience. Agencies can consider the effect of maintaining "as-is" or implementing resilience approaches. Making this comparison could support requests for increased resilience funding by showing the positive impacts of resiliency investments on future conditions. Table 6-4 can be used to check off actions an agency has already taken to integrate resilience to extreme weather events and climate change into the transportation asset management process, and to prioritize remaining actions. Chapter 8 addresses this further, where the impacts of mitigation strategies are evaluated over the life-cycle of assets.

Table 6-4. Checklist of Potential Actions on Integrating Resilience Into the Objectives,Measures and Targets for Transportation Asset Management

Complete?	What to analyze?	What to include?
	Determine whether extreme weather events and climate change will affect the agency's ability to meet objectives.	Modify existing objectives or develop new objectives that address climate resilience challenges.
	Determine whether existing measures and targets are adequate given extreme weather events and climate change or changes to agency objectives.	Modify existing measures and targets or develop new measures and targets that address increasing the resilience of specific vulnerable assets.

7 Establish Risk Management Process

As agencies establish a risk management process as part of transportation asset management, they can analyze the risk of potential damages from extreme weather events and climate change to develop associated approaches to manage risk and to invest in the system. Extreme weather events, which may be exacerbated by climate change, have the potential to create significant cost implications both for transportation agencies and transportation system users.

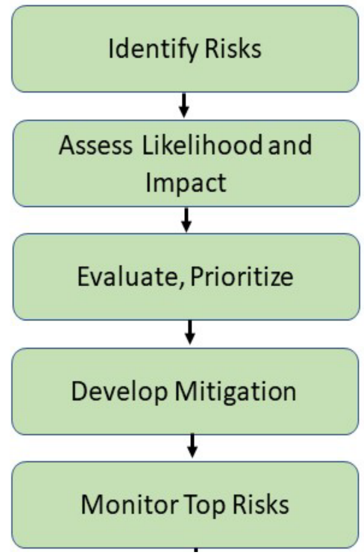

Figure 7-1. Steps in the FHWA risk management process, edited. (FHWA, 2012)

There are five steps common to most internationally recognized risk management frameworks (see Figure 7-1). The process starts with identifying risks that could affect asset condition, which could result from many factors. In the resilience context, risks may include extreme weather events, climate change and seismic activity. Assessing the likelihood and impact/consequence of the occurrence of that risk could rely on previously conducted (or new) vulnerability assessments to prioritize the locations and identified risks. Ranking could include sorting the sites based on data included in the vulnerability assessment (see *Chapter 3: Understand Vulnerability to Extreme Weather Events and Climate Change*) or using data such as criticality or functional classification. Mitigation plans can be developed to address the top priority risks. The final step involves developing a process to monitor each risk or site as identified.

The risk management process is most useful if it influences other elements of transportation asset management, such as the investment strategies and financial plan (see *Chapter 9: Establish Resilient Investment Strategies and Financial Plans*). The following sections describe how extreme weather events and climate change could be incorporated into risk management processes.

Risk Management Process and the TAMP

As part of developing the risk-based TAMP, State DOTs are required to establish a process to develop a risk management plan that: identifies risks that can "affect condition of NHS (National Highway System) pavement and bridges and the performance of the NHS, including risks associated with current and future environmental conditions, such as extreme weather events, climate change…and risks related to recurring damage and costs as identified through the evaluation of facilities repeatedly damaged by emergency events carried out under part 667 of this title" (23 CFR 515.7(c)(1)).

[As of October 21, 2021, State DOTs are required to consider extreme weather and resilience as part of the lifecycle cost and risk management analyses within a State TAMP (23 U.S.C. 119(e)(4)(D)). As noted in the Executive Summary, this handbook does not address implementation of this provision from the BIL.]

7.1 Coordinate the Vulnerability Assessment with the Risk Management Process

The vulnerability assessment has some similarities, and important differences, from the risk management process in transportation asset management. Both involve identifying potential hazards or threats and developing strategies to address them.

In the context of resilience, risks are often assessed as a product of the likelihood that an asset will experience a particular hazard or stressor, and the consequence of that impact. The vulnerability assessment examines exposure, sensitivity, and adaptive capacity to environmental hazards, such as flooding, storm surge, sea level rise, higher temperatures, and wildfire, and can be a useful input for assessing the likelihood and consequences of environmental risks. Specifically, exposure data can inform the likelihood of impact, and sensitivity and adaptive capacity data can help determine the severity of consequences. For example, an asset that is highly sensitive to flooding would generally experience more severe consequences than an asset that has flood proofing measures in place. Similarly, an asset that is projected to be exposed to sea level rise in the near term has a higher likelihood of experiencing that hazard, compared to one that may not be exposed until the end of the century.

The risk assessment can include natural hazard risks but also can be broader and include financial risks, risks caused by staff turnover, political events, changes in technology, or strategic risks such as environmental compliance. Each agency will decide how to integrate the vulnerability assessment with its other risk management efforts. Options include:

- Conducting both the vulnerability assessment and the asset management risk analysis under the direction of a single agency decision maker to ensure coordination of efforts.
- Including team members from the vulnerability assessments on the larger risk assessment team.
- Jointly developing strategies to reduce identified vulnerabilities along with the agency's risk mitigation strategies.
- Including the vulnerability assessment risks and mitigation steps in a risk register.

Viewing the vulnerability assessment and risk management efforts as complementary can help agencies be better prepared to anticipate and respond to risks, in all forms.

7.2 Develop Risk Statements for Extreme Weather Events and Climate Change

The risk team (inclusive of asset management and environmental/resilience staff) can develop a set of risk statements related to extreme weather events and climate change based on the results from the agency's vulnerability assessment (*Chapter 3: Understand Vulnerability to Extreme Weather Events and Climate Change*) and any subsequent work completed as part of the asset management planning process. The vulnerability assessment can serve as a screening exercise to narrow the combination of hazards and assets that risk statements address. For example, if a large number of bridges were identified as vulnerable to storm surge, then that would be captured in a risk statement.

Benefits of Risk Statements

Risk statements provide several benefits, including:

- *Enumerate the risks* that your agency faces.
- *Spur discussion* among stakeholders who may not initially assume their work unit or priorities may be affected by a risk.
- *Stimulate thinking* about risk mitigation, which is discussed in Section 7.4.

Risk statements are often written in the form of "if-then" statements. For example, "If sea levels increase as projected, then low-lying coastal assets will be inundated more frequently during high tide events, and the extent of inundation during high tide events and coastal storms will increase, leading to travel disruptions and increased asset deterioration."

It can be helpful when writing risk statements to fully articulate the risk with a subject, verb, and object. The many implications of sea level rise are not identified when only the topic is listed. One risk can be used to generate many risk statements. For example:

- Sea level rise could impede emergency responses during events.
- Sea level rise could accelerate asset deterioration.
- Sea level rise could increase costs to maintain a state of good repair.
- Sea level rise could cut off agency facilities during emergencies.
- Sea level rise could endanger the public as well as operations and maintenance staff.
- Sea level rise could cause bridges or bridge approaches to overtop at an unacceptable frequency.

When each of these is expressed as a separate risk statement, they can be used later to help prioritize the responses. If one impact is much greater than others, it can allow focusing limited resources on the most critical mitigation responses. Also, the "risk owner" may vary depending upon the hazard's effect.

It is appropriate to distinguish "systemic" risks from risks to individual assets, facilities, or classes of assets (see the vulnerability categories discussion in *Chapter 4: Develop Asset Inventory*). Systemic risks are more likely to be caused by gradual changes in temperature and precipitation patterns rather than individual extreme events like storm surge or geographically constrained risks like sea level rise. A systemic or network-wide risk could be increased temperature and its effect upon flexible pavement rutting or concrete pavement "blow ups." This general risk may be mitigated through pavement designs such as "stiffer, drier" asphalt designs, more use of high-temperature binders, or, in rigid pavements, shorter joint spacing or enhanced load transfer (FHWA, 2015c). As the term "systemic" implies, these risks may be addressed through agency-wide or multi-agency policies, strategies, or standards.

It is also appropriate to develop risk statements for specific critical assets, or classes of asset identified as vulnerable (see *Chapter 3: Understand Vulnerability to Extreme Weather Events and Climate Change*). These assets generally are uniquely sensitive because of their age, material, or location. An example could be a tunnel in a low-lying coastal area that will be exposed to sea level rise, increased storm events, or storm surge. Another could be specific roadway sections in floodplains, or sections susceptible to slope failures, or pavements on expansive soils.

The specificity in a risk statement can enhance subsequent risk mitigation analysis. A risk to a specific asset may generate a specific risk mitigation response. If a bridge is scour critical, or a pavement frequently inundated, it generates a specific response. Similarly, a vulnerable asset on a key evacuation route that lacks a redundant or parallel evacuation route may warrant hardening or could lead to developing a redundant evacuation route.

7.3 Risk Management: Evaluate Likelihood and Consequences in the Context of Current and Future Environmental Conditions

Risk management involves analyzing the likelihood and consequence associated with risks and plays a critical role in risk-response strategies, or risk mitigation. Some risks are of high consequence but low likelihood, such as 500-year storm events or a high-magnitude earthquake. Other risks are more "chronic," and have high likelihood but relatively low consequences, such as annual minor flooding or periodic, minor rockfalls from unstable slopes. As discussed below, agencies can use the combination of likelihood and consequence to measure and compare dissimilar risks for prioritization.

Likelihood and consequences can be assessed with the help of a risk matrix such as from the *AASHTO Guide for Enterprise Risk Management* (see Figure 7-2), a voluntary guide that is not required under Federal regulations. Use of a risk matrix can support analytical consistency across risk categories.

Liklihood	Values	Risk Scores			
Almost certain	5	5	50	200	350
Probable	4	4	40	160	280
Possible	3	3	30	120	210
Rare	2	2	20	80	140
Exceptionally rare	1	1	10	40	70
		Value/Consequence Relationship			
		1	10	40	70
		Low	Moderate	High	Severe

Figure 7-2. Risk matrix from the AASHTO Guide for Enterprise Risk Management (AASHTO, 2016).

Figure 7-3 highlights another example of a risk matrix from CAMPO (TX) (CAMPO, 2015). This summary risk matrix plots the relative risk of flooding, drought, extreme heat, wildfire, and extreme cold for a segment of State Highway 71 east. Each stressor is plotted based on the likelihood of exposure and consequence.

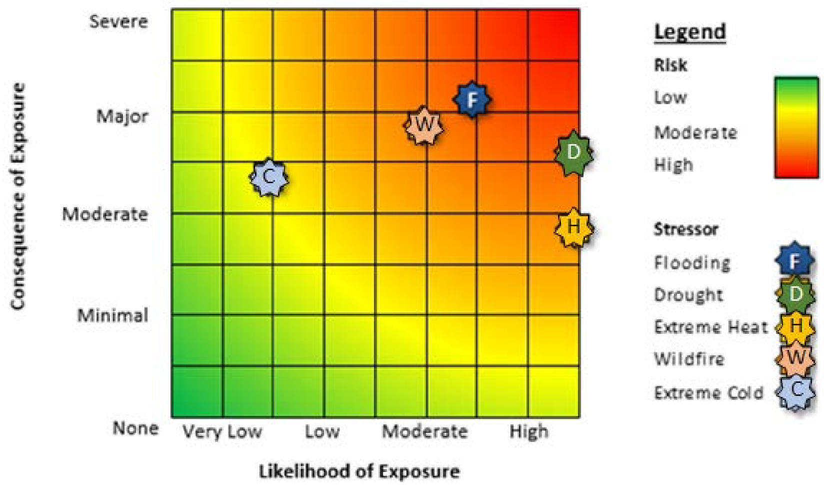

Figure 7-3. CAMPO risk matrix for State Highway 71 East at State Highway 21 (CAMPO, 2015).

There are several ways to identify likelihood and consequences, similar to the approaches outlined for conducting vulnerability assessments in *Section 3.3: How resilient is the transportation system?*. Conducting workshops with informed stakeholders is the most common way, although online tools or other virtual means to solicit and consolidate responses from stakeholders also are sometimes used. Because of the specific nature of risk attributed to changing environmental conditions, the components of the vulnerability assessment (*Chapter 3: Understand Vulnerability to Extreme Weather Events and Climate Change*) can inform an agency's understanding of likelihood and consequence. The information in those assessments can help stakeholders understand the potential frequency, or likelihood, of some risks as well as their consequences.

Tool: RAMCAP Framework

Another tool for addressing physical threats to assets is the Risk Analysis and Management for Critical Asset Protection (RAMCAP) framework. It is a framework for quantifying the likelihood and impacts of physical events such as floods, seismic events, or slope failures on infrastructure. The Colorado and Utah DOTs have used it for corridor risk analysis to estimate when risk mitigation treatments can be economically justified based upon the potential for future asset failures. See the Adaptive Mitigation Case Study textbox in *Section 7.4* for additional details.

The preceding section discussed the benefit of developing multiple, and specific risk statements to help clarify and focus risk responses. The vulnerability assessment can also help clarify and focus the assessment of likelihood and consequence to different risk statements. For example, it is common for likelihood and consequence to vary across a State for the same class of assets. The vulnerability assessment can help identify what types of assets in each geographic area are most at risk.

Climate change can also exacerbate other risks

When considering likelihood and consequence, agencies also may consider risk statements that are not directly related to natural hazards, but may be compounded by climate change. For example, financial risks to programs may increase in parallel to the increase in environmental risks. Increasing environmental risks can require more emergency response funding, which can divert resources from investment in regular asset programs. Increased storm events can tax finite resources of maintenance crews who are then unable to perform routine preventive maintenance. Or, increased events may accelerate asset deterioration, which increases costs over time. In summary, changing environmental conditions can create secondary impacts that exacerbate other types of risks.

Likelihood

Likelihood is typically defined on a common scale across risks; however, there are some unique considerations for current and future environmental conditions. The likelihood is the (annual) probability of an event to which an asset is vulnerable, but that probability may be increasing in a region where an agency is located. There are several relevant considerations when determining likelihood, as described below.

Timeframe: Transportation agencies can take a long-term approach to manage assets over their entire life-cycle. Agencies can choose an analysis period that is similar to a life-cycle cost analysis period, which is equal to asset service life. For bridges, that would typically be about 75 years. Although the likelihood is usually reduced to an annual probability (e.g., the 1% annual probability storm event), the cumulative probability over the timeframe in question is also relevant to risk analyses. Over a longer timeframe, assets are more likely to experience extreme weather events. For example, the likelihood of a 1% annual probability storm occurring is greater over a 30-year planning horizon than a 10-year horizon. When considering the effects of climate change, it is particularly important to consider a longer timeframe. Risks from environmental conditions that may not have been historically relevant or concerning for the transportation system in the short term may become more frequent or severe over the service life of system assets. (USGCRP, 2018).

Changing likelihood: In many locations, extreme weather events (including precipitation events and heatwaves) are projected to become more frequent and intense in the future (USGCRP, 2018). For example, today’s 10-year precipitation event may become a 2-year event in the future; similarly, a 10-year event in the future may have greater precipitation associated with it than today’s 10-year event (local conditions may vary). When considering likelihood, it is necessary to consider not only how frequently extreme weather events have occurred in the past, but also how likely they are to occur in the future.

Gradual changes: Gradual changes in environmental conditions, such as temperature increases and sea level rise, will affect transportation agencies (FHWA 2020; USDOT 2008). Consider integrating thresholds in the risk statements for these types of hazards to better allow the qualitative assignment of likelihood. For example, an average summer maximum temperature of five degrees higher than historical averages may have a low likelihood in the near term and under a low emissions scenario, but a higher likelihood over a longer timeframe under a higher greenhouse gas emissions scenario. It is their consequences that will vary over time from relatively minor to more severe (USGCRP, 2018).

Future scenarios: There are a range of climate change scenarios; those often used by DOTs and others in resilience assessments are the Representative Concentration Pathways (RCPs) (see USGCRP, 2018). No one RCP is considered more likely than any other RCP (though lower scenarios seem less and less likely as greenhouse gas concentrations continue to rise), making it difficult to assign probabilities. Instead, for the purposes of a risk assessment, agencies may select a higher scenario (e.g., RCP 8.5) and/or a lower scenario (RCP 4.5) for determining likelihood and consequences of extreme weather events and climate change. While a high scenario is appropriate for screening risks, the risk mitigation measures should be tested for their impacts and cost effectiveness across a range of possible futures. Information on future climate projections is available in the NCA4 report (USGCRP2018); projections for different areas can also be accessed from several websites: NOAA's Climate Explorer (NOAA 2020) and FHWA's CMIP Climate Data Processing Tool (FHWA, 2020).

Consequences

The determination of consequence is a two-step, or even iterative process. First, the consequence of unmitigated risks is determined. Then, the risk mitigation phase of the analysis considers how the consequence can be reduced through mitigation. The difference in benefit between the unmitigated consequences and the mitigated consequences, combined with the difference in the construction/operation costs, provides the metrics for selecting which mitigation strategies to adopt. (One reason why it is important to consider potential consequences is that consequences can affect a State's ability to meet its targets for relevant performance measures, as discussed in chapter 6.)

Cost Comparison

Different risk mitigation strategies can be compared based upon the potential cost of damage (direct and indirect) to an asset over its expected service life compared to the cost of improvements to mitigate or avoid the potential damage.

Adaptive capacity information from the vulnerability assessment can provide agencies with a sense of the qualitative consequences associated with a given extreme weather event. For example, assets that have high traffic levels, serve as detours or evacuation routes, serve as lifelines to essential services, or have a high replacement cost, represent greater consequences to the ability of the DOT to achieve its mission.

Consequences can also be quantitatively calculated. The quantitative impact or consequence is the expected user and agency cost of damage and disruption for each event. For example, if a bridge is hydraulically deficient for the 1% annual probability storm and has 50 years of service life remaining before replacement, and the agency and user cost associated with each 1% event is $100,000, then the annualized cost is $1,000 (1% of $100,000) and the cumulative cost is $39,500.[3] That assumes the replacement structure is designed to accommodate the 1% annual chance storm and there is no remediation cost after replacement. In the future, remediation costs may be higher as extreme weather event intensity increases and therefore damages may increase. These costs can be translated to present values to account for the time value of money. This type of information is valuable to compare bridges for tradeoff analysis, and also to consider in combination with other work to determine the most cost-beneficial timing of a project.

Ideally, all relevant consequences should be evaluated and included in the analysis, including the cost to restore an asset, the consequence of the loss of an asset during an emergency, and the long-term service disruption caused by damaged assets.

- An example of a **high-cost consequence** would be frequent inundation of a system interchange that could stop travel on two or more high-volume facilities. The cost of elevating or otherwise making the system interchange less vulnerable could be quite expensive, raising the consequence of the impact both in terms of financial cost to the agency and service interruption to the transportation network, and thereby raising user costs. Low-lying interchanges or freeway sections can be considered an important part of freeway facilities whose long-term upgrade may involve years of advanced planning to design, finance, and harden.
- Some asset failures may trigger costs associated with **regulatory non-compliance**. Drainage assets such as retention/detention ponds, outfalls, and catch basins that fail or sustain damage during events can cause an agency to incur costs associated with citations. In this example, the consequences are not only in terms of cost but also in terms of regulatory compliance, environmental impacts, and agency reputation.
- Another type of consequence is **loss of key routes during emergency events**. Key evacuation routes or the routes that could serve as key detours if major routes or structures are damaged may be worthy of identification and treatment to ensure their resilience. Even temporary loss of service of these facilities can exacerbate the consequences of storm events and other disasters.
- **Loss of service also can occur during non-emergency events**. For example, if the 10-year precipitation event in a particular area is now producing more flooded areas and temporary closures, locations that are susceptible should be considered as they may affect long-term plans and management of those facilities. For example, when a project is

[3] The probability of at least one storm over any given time period is 1-(1-1/T)^n where T is the return interval (e.g., 100-years for a 1% annual chance storm), and n is the number of years in the time period (e.g., 50 years in the example scenario). In the example scenario, the probability of a 1% annual chance storm occurring over a 50-year time period is 39.5%, so the cumulative cost is $39,500. Note that this calculation does not account for the increasing likelihood of extreme weather events due to climate change. (USGCRP 2018)

considered to rehabilitate a bridge that is known to commonly overtop, the project analysis should compare the benefit and cost of rehabilitation versus replacing with a functionally improved bridge that does not overtop as frequently. If replacement proves to be cost effective, the agency may decide to replace now or temporarily shelve that project allowing the bridge to deteriorate further until replacement is needed.

- **Loss of service to operational support infrastructure** represents another type of consequence. Key operational units such as transportation management centers (TMCs) could be vulnerable to power outages, inundation, or wind damage during hurricanes and other events, and thus could be considered critical assets to the performance of the NHS and worthy of hardening or redundancy.
- The **consequences can vary** depending on the location of the impacted infrastructure. For example, disruptions to public transportation may cut off the only means for disadvantaged communities to get access to essential services while other communities with greater resources may not be impacted as much.

In summary, when considering the impacts of current and future environmental conditions on assets, the consequences can be broad and could include not only cost, but critical service and safety functionality impacts. Agencies can document risks by asset class/subgroup and the extreme weather risks and expected change in those risks associated with each grouping in their risk register. Also, agencies can use their risk register to document locations that are at higher risk of climate change.

7.4 Develop Risk Mitigation Strategies

Resilience-focused risk mitigation strategies build from the risk statements (*Section 7.2*) and risk assessments (*Section 7.3*) and are often included in a risk register. There is no single recognized format for a risk register, but they generally include the risk statement, the risk owner, the mitigation strategy and its timeframe, and possibly the status of the risk mitigation strategy.

Consider Using Asset-Level Analyses to Build Decision Trees

Detailed risk assessments typically are performed at the asset-level; however, as more and more projects go through extreme weather risk analyses, patterns or "rules of thumb" for understanding and addressing risks may emerge. Over time, consider establishing decision risk management trees to quickly determine the best risk management strategy for particular assets. Decision trees used for risk management usually compare the expected value of different risk mitigation options based upon their costs and their probabilities of success.

Risk mitigation strategies are generally brief statements intended to catalyze actions an agency will pursue to reduce risks. Risk mitigation strategies could focus on specific assets, asset classes, or the network as a whole, and may be proactive, reactive, or oriented toward ongoing monitoring. Whether risk mitigation should be proactive or reactive depends on the predictability of events.

It may also be useful to consider developing risk mitigation strategies focused on the needs of disadvantage communities.

Proactive risk mitigation strategies are preferable when the likelihood of risk occurrence is high, and the consequences of the risk are moderate to high. In these situations, impacts can be anticipated with some confidence. These strategies may also be appropriate for particularly high-cost, high-traffic, or high-profile assets such as major bridges, transit hubs, system interchanges, or high-volume freeway sections.

Table 7-1 shows an example risk register with proactive risk mitigation strategies and implementation details for a storm surge event.

Opportunistic Risk Management

Agencies can establish a process to flag potential opportunities to address extreme weather events and climate change during the project development process. For example, MDOT SHA developed a project screening tool using the results of its vulnerability assessment to take advantage of existing repair or replacement projects as they enter the pipeline. If an asset is flagged as exposed and sensitive to a hazard in the vulnerability assessment, the screening tool prompts MDOT SHA to gather additional information on risk factors and consider how changing risks should be factored into project development. For additional information, see page 22 of *Integrating Extreme Weather and Climate Risk into MDOT SHA Asset Management and Planning* (MDOT SHA, 2019).

Table 7-1. Example Risk Register

Risk Statement	L *	C †	Rating	Owner(s)	Mitigation	Timeframe	Status
Higher storm surges will increase the frequency and duration of pavement inundation in our coastal areas, leading to increased pavement deterioration.	5	40	200	Pavement modelers	Track changes in pavement conditions to determine if increased deterioration accompanies increased inundation.	By Dec. 31, 2022	Analysis of deterioration rates under development.
				Design staff	Develop design plans for mitigation including enhanced drainage, selected roadway section elevation.	By July 1, 2025	Roadway sections under analysis for prioritization. Design manual update under way.
Higher storm surges will increase the frequency and duration of pavement inundation in our coastal areas, leading to increased road closures and service interruptions.	5	40	200	Maintenance engineer	Develop quick response plan for each section subject to flooding to establish closures, and post-event cleanup protocols.	By Dec. 31 2020	Each affected garage developing its draft response plan by June 1, 2020.

* Likelihood
† Consequence

For hazards that are less predictable or consequential, a **reactive** approach may be warranted. For example, future locations of fires in dry, forested states are difficult to predict because they can be caused by random events such as lightning strikes or human error. But even reactive approaches can be planned for in advance. For unpredictable events or low likelihood events, a reactive strategy may be advisable. Examples include:

- Contingency funds set aside for emergencies as part of the financial plan.
- All hazard protocols that allow quick response regardless of incident type.
- Periodic tabletop exercises to strategize how to respond to an unpredictable event.

Colorado Adaptive Mitigation Case Study

The FHWA worked with Colorado DOT to conduct a case study on how to mitigate the risk of failure to a culvert on a key section of U.S. 34. The FHWA conducted an alternatives and tradeoff analysis to evaluate options for making the culvert resilient to increased rainfall and the potential of increased runoff, sedimentation and debris flow caused by potential forest fires on adjacent slopes (FHWA, 2017e). The analysis examined a low, medium, and high precipitation scenario.

The analysis concluded that it would be too costly to retrofit multiple culverts to accommodate both the highest precipitation scenario combined with sedimentation and debris flow resulting from a potential fire. The recommended alternative was to size the culvert for the moderate runoff scenario while making the culvert expandable in the future if a fire occurred in the watershed. If a fire were to occur, measures to naturally stabilize the burned slopes and remove excess debris would also help to protect the culvert in the event of a flood.

The proposed solution includes both a proactive alternative and the reactive option to add enhanced capacity if needed in the future.

Finally, in cases where the risk is beyond an agency's control, the mitigation strategy may be to **monitor the risk and prepare contingency plans** for responding to the risk should it occur. Monitoring risk is also a useful strategy for lower priority risks that may warrant a response in the future. See *Chapter 10: Develop a Monitoring Plan to Track Risks Related to Extreme Weather and Climate Change* for more details.

For more information on potential risk mitigation strategies, see:

- FHWA Synthesis of Approaches for Addressing Resilience in Project Development, which provides examples on various types of transportation assets and associated strategies.
- Chapter 5 of FHWA Vulnerability Assessment and Adaptation Framework, which provides information on types of strategies as well as approaches to evaluating and prioritizing options.

Consider including in the TAMP Risk Management Plan: A list of risk mitigation strategies for the top-priority risks. Develop proactive and reactive risk mitigation strategies. Organize mitigation strategies in a risk register table that includes the top risks, likelihood, impact, risk owner, and risk mitigation strategy. Note that one risk event can cause a variety of impacts, which may warrant a series of risk statements and mitigation strategies.

7.5 Recap of Integrating Resilience into the Risk Management Process

The risk management process provides a logical framework for assessing and monitoring extreme weather risks and climate change, and for tracking how they are being managed. These risks can "nest" neatly within the overall risk management process and can complement the risk-based asset management process. The risk-management process provides a consistent way to assess the likelihood and consequence of dissimilar risks to allow objective decisions on which of the many risks merit the most attention and investment. It also provides a logical complement to larger performance-management processes. As agencies focus upon delivering its performance objectives, they can report on how they are managing the risks that could impede the performance. Table 7-2 can be used to check off the actions that agencies have already taken to integrate resilience to extreme weather events and climate change into transportation asset management and prioritize remaining actions.

Table 7-2. Checklist of Potential Actions on Integrating Resilience into the Risk Management Process for Transportation Asset Management

Complete?	What to analyze?	What to include?
	The risk management process includes the following steps that help to prioritize adaptive strategies to reduce the threat of environmental hazard impacts • Use a multi-disciplinary team to identify risks and develop detailed risk statements. • Identify hazard/environmental risks that are often observed during project development and scoping such as flooding. Generally, these types of risks impact a good portion of an asset class, therefore, risks such as flood risk should be elevated to the network level analysis. • Assess each risk statement by its likelihood and consequences. • Prioritize risks because some can be influenced by the agency and others may be beyond its control and only subject to monitoring, not managing. • Develop risk mitigation strategies. • Develop a risk register to track and report on risks. • Use the risk register as a component of a monitoring plan to stay abreast of how risks, and risk responses, evolve over time.	• Include current and expected future extreme weather events and climate change risks in the risk register. • Develop a list of risk mitigation strategies for the top-priority risks • Factor exacerbation from extreme weather events and climate change risks into the likelihood and consequence ratings for other items in the risk register. • Include risk mitigation strategies that address specific risks that are often identified during project development scoping but calls for a network wide action such as treatment of eroded embankments.

8 Develop Life-Cycle Plan

Life-cycle planning lies at the heart of asset management. To develop effective life-cycle strategies, agencies need to understand how future weather events will influence asset condition and performance including functional adequacy. Deterioration curves based on historical performance may not accurately capture how assets will perform under future temperature, precipitation and sea level conditions; sound life-cycle planning involves consideration of changing environmental conditions affected by climate change over the life of assets.

The analysis of climate- and weather-related risks outlined in prior chapters can strengthen the life-cycle planning process, which is foundational to transportation asset management's focus on sustaining a desired state of good repair over the life-cycle of assets. Climate change can be an important influence on how an asset performs, the cost to maintain it, and how frequently it needs to be treated. While increased risk of significant damages from extreme weather events and appropriate mitigation strategies were addressed in *Chapter 7: Establish Risk Management Process,* changes in gradual deterioration due to changing environmental conditions is best addressed in the life-cycle plan. (One caveat: roads and bridges face both extreme weather events and climate change, as well as sudden damage and gradual deterioration; separation of damage and deterioration is somewhat artificial as the two may well interact together on the same asset or asset class.) For example, key decision tools such as bridge deterioration curves can be

Life-cycle cost and life-cycle planning in the TAMP

Life-cycle cost means the cost of managing an asset class or asset sub-group for its whole life, from initial construction to its replacement. (23 CFR 515.5)

Life-cycle planning means a process to estimate the cost of managing an asset class or asset sub-group over its whole life, with consideration for minimizing cost while preserving or improving the asset condition. (23 CFR 515.5)

Life-Cycle Plan: 23 CFR 515.7(b) requires State DOTs to establish a life cycle planning process for an asset class or asset sub-group that should "include future changes in demand; information on current and future environmental conditions including **extreme weather events, climate change…**, and other factors that could impact whole of life costs of assets."

The TAMP must describe how the NHS will be managed to achieve system performance effectiveness and State DOT targets for asset condition in a fiscally responsible manner, at minimum practicable costs over the life cycle of its assets. (See 23 CFR 515.7)

[As of October 21, 2021, State DOTs are required to consider extreme weather and resilience as part of the lifecycle cost and risk management analyses within a State TAMP (23 U.S.C. 119(e)(4)(D)). As noted in the Executive Summary, this handbook does not address implementation of this provision from the BIL.]

strengthened by applying an environmental modification factor or changing an asset's environmental factor if the environment changes. For pavements, because environmental factors are not typically included in deterioration models, a first step would be to assess environmental stressors (such as sea level rise) and begin tracking and accounting for deterioration rate changes within those stressed locations.

Asset classes to consider in life cycle planning:

- Pavements
- Bridges
- Tunnels
- Hydraulic structures
- Embankments
- Maintenance facilities
- Safety barriers and signs

As discussed in *Section 3.2: How are the hazards changing?*, although a financial plan may cover a shorter period of investments, it is really a subset of a longer program of investments over the full life-cycle of asset classes or subgroups. Consider potential investments 20 to 40 years (minimum) into the future to better reflect the range of needed investments over the life-cycle of the different asset classes and subgroups. When the analysis period is extended, a more accurate picture of life-cycle costs will be evident, and the risk of climate change can be better captured. Similarly, a longer analysis period for major assets such as NHS pavements and bridges could indicate a return on resilience investments that may not be apparent over a shorter timeframe. An example could be raising the elevation of a bridge approach and expanding its waterway opening. When potential flooding over the service life of a bridge is considered, the investment may provide substantial returns in terms of reduced agency/budget and user costs when service interruptions are estimated. The life-cycle planning process should be extended as appropriate to better reflect the entire life-cycle of assets within each asset class to capture the environmental changes expected over that time frame.

8.1 Determine How Extreme Weather Events and Climate Change Could Affect Usefulness of Assets

Before investing in an asset today, agencies would benefit from understanding the long-term plan for that asset considering climate change. This goes beyond the direct impact of natural hazards on assets, as discussed in other chapters, and includes considering broader changes in communities and regions resulting from climate change that ultimately affect demand for transportation services. For example, increasing impacts such as flooding in low-lying areas can slowly begin to reduce traffic. Agency choices include: increasing investment in maintenance activities, investing in protective measures, adding redundant roads, abandoning and relocating transportation assets, and in some cases relocating whole communities (sometimes referred to as managed retreat). (FHWA, 2020b). Before making investments, an agency may want to consider the level of investment necessary to keep assets operating for their full service lives, or in some cases, if assets will even be needed in future decades. Such considerations could significantly influence life-cycle planning decisions, and help to avoid stranding investments in areas that may have to be abandoned or relocated.

Agencies should carefully consider the risk of stranded assets. Investing in infrastructure may not be fiscally responsible if the land uses surrounding the asset change or traffic generators are abandoned due to extreme weather events and climate change. A decision to abandon assets should consider the potential adverse impact on a surrounding community, particularly in cases where limited alternatives exist. While this change will not happen overnight, it is feasible over the life of transportation assets. For example, some agencies are considering the strategic abandonment of selected portions of their NHS when the traffic levels are low, redundancy is high, and the risk of extreme weather damage is also high.

The Rhode Island DOT (RIDOT) asset management plan strongly emphasizes the agency's incorporation of climatic threats and sea level rise into its life-cycle planning. A statewide planning study forecasts that by 2100, Rhode Island could experience up to 10 feet of sea level rise. The Rhode Island plan notes that bridges built in 2019 will be almost halfway through their life-cycle by 2050—but by then sea levels could rise by three feet. The RIDOT plan indicates that planning for such impacts should occur when treatments to assets are considered. The results of RIDOT's sea level rise study will be used to consider the realignment, elevation, or alternative route construction of potentially affected facilities when treatment or replacement of those facilities are considered. (RIDOT, 2018).

The Rhode Island example illustrates the need for DOTs to communicate with regional and local agencies to understand their anticipated future need for potentially vulnerable transportation assets. Planning can involve not only State and Federal environmental agencies, but also local governments that control land uses. As RIDOT illustrates in Figure 8-1, the increasing rise in sea levels will follow new assets throughout their design life. For new assets in the RIDOT coastal zones, sea level rise has become a significant planning factor along with future traffic projections and land uses.

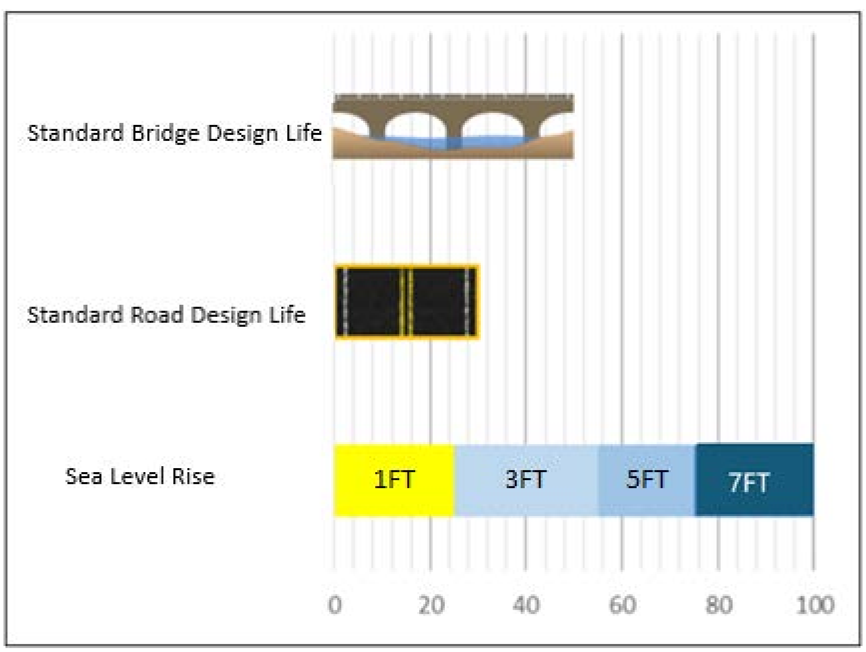

Figure 8-1. Life of bridges and road design compared to sea level rise projections in Rhode Island (RIDOT, 2018).

8.2 Integrate Extreme Weather Events and Climate Change into Management Systems and Other Analytical Tools

Management systems – including those for bridges, pavements and culverts – can assist transportation agencies in selecting and performing work that is the most cost-effective for individual assets and the inventory as a whole. Their optimization procedures assist in identifying strategies and programs of projects that will maximize benefits subject to budget constraints, minimize costs subject to performance constraints, and by varying the constraints they provide for comparison of multiple strategies to identify the tradeoffs between budget and performance level.

Management systems can help agencies achieve their performance objectives and goals and maximize returns on investment. Climate change can alter how State transportation agencies approach the development and use management systems and other analytical tools. While some management systems can consider historic environmental conditions, it is important to note that forecasts developed based on historic weather alone may not be sufficient for assessing future climate conditions; projected climate conditions based on future trends can more accurately predict impacts to asset conditions over their service lives.

Bridge management systems

In some bridge management systems, structures can be grouped in climatic zones. As climatic conditions change over time, agencies may want to consider whether structures are grouped in the correct zone. While climatic zone does influence bridge deterioration rates, largely related to humidity and freeze/thaw rates, differences in climate and the effect on deterioration are normally only discernable when viewing a large geographic region.

As agencies analyze historical condition data to determine deterioration rates, that data will be representative of the climatic zone(s) that encompass each agency's jurisdiction. One effect of climate change is that it may gradually shift the climatic zone. In addition, site-specific factors reflect situations that are unique to a bridge and its immediate location. Example factors include frequency of wetting by high water, waterway spray, or traffic spray, frequency of salt application, frequency of preventive washing and cleaning, number/type/condition of deck joints, bridge grade and features that affect drainage, etc. It is expected that changing environmental conditions will affect some site-specific factors.

When collecting condition data and developing deterioration models within bridge management systems, agencies can develop and incorporate environmental severity factors. Bridge management system analyses generally incorporate the AASHTO element condition data inspection standard that recommends assignment of an environmental severity within one of four categories – benign, low, moderate, or severe (AASHTO, 2019). When analyzing condition data, bridge owners should determine if there are differences in deterioration rates across regions within their jurisdiction and should assess the site-specific factors that affect deterioration. After assigning environmental severity factors and including them within deterioration models, agencies should periodically determine if the assigned factors need updating to reflect future environmental conditions the assets are expected to experience. As deterioration modeling practice advances, some agencies may also find the need to increase the number of environmental severities beyond the usual four that are currently used in bridge management system analyses to provide more granularity. An acceptable approach to doing this within the existing standard for element-level condition data collection is to break each of the four severities into subcategories.

Culvert management strategies

For culverts, important management strategies include the following:

Project vs. Network Level Planning

While risks and costs of inaction for bridges are typically assessed at the project/asset level, project level findings are also a critical input to network level planning for bridges. For example, the most cost-effective life-cycle strategy for a bridge will be a function of many site dependent factors and the relative condition and remaining service life of the individual components or elements. Also, costs calculated for individual bridges can be rolled up to the network level to inform decision-making. Individual analyses are also useful for identifying common issues across individual assets that may need to be addressed at the network level. System redundancy, or lack thereof, can influence the importance of individual bridges; user cost analysis can influence the value or expected benefits of keeping individual bridges in service.

- Determine most needed data to inform decisions and standardize methodology prior to data collection.
- Locate and inspect culverts and keep the information stored in a GIS database.
- As needed, decide on inspection protocols and establish consistent methods to rate the culverts.
- Coordinate possible actions on culverts (e.g., replace, line) with pavement rehabilitation projects to avoiding cutting pipe trenches in good pavements.

- If possible, plot hydraulic performance curves of culverts to see how much resilience they have built in before they violate allowable headwater conditions, or worse, overtop the road or flood properties. If worried about future precipitation increases, this analysis (Hershfield, 1961)Connecticut DOT (2014) conducted a pilot study to test the hydraulic

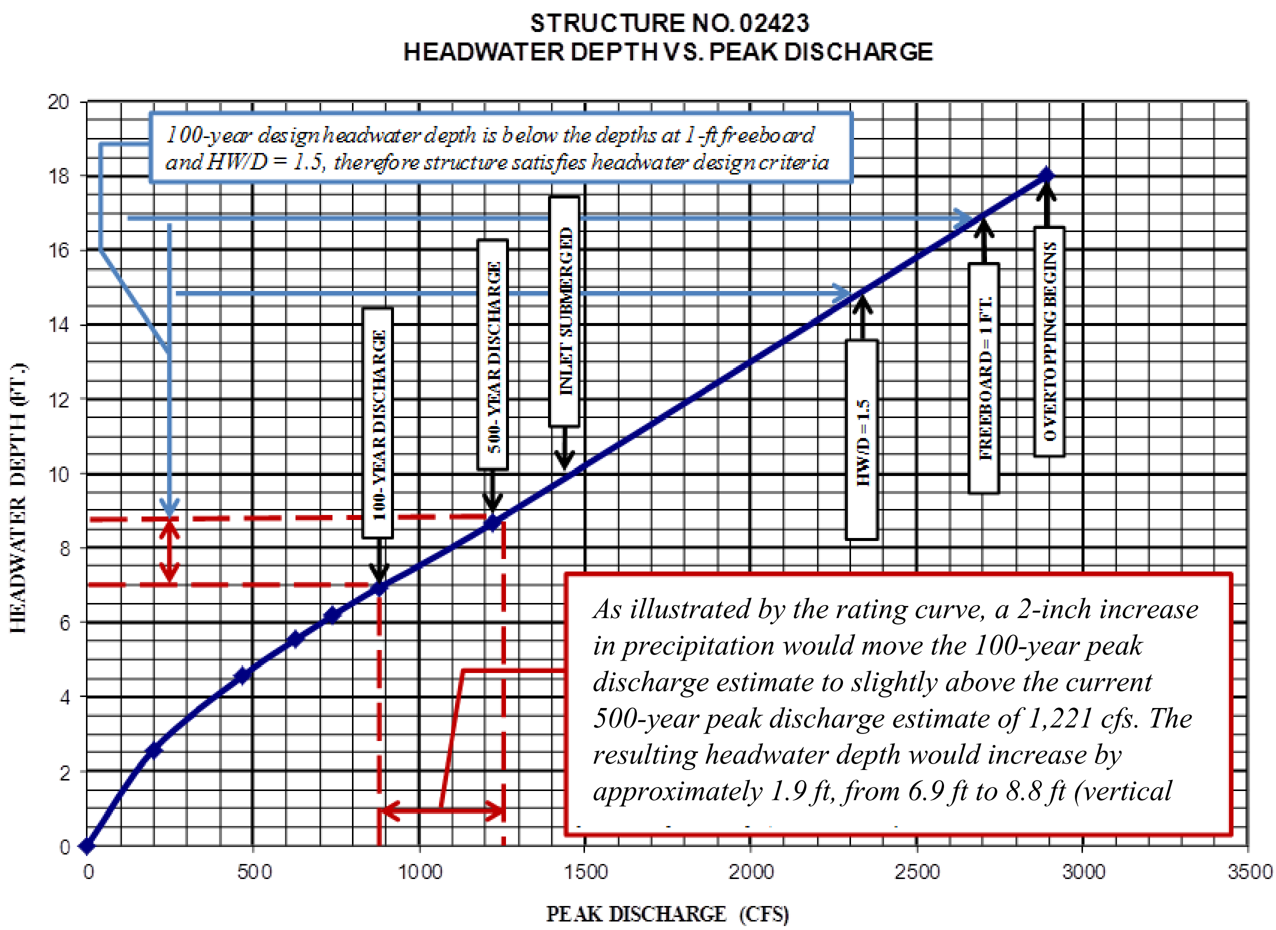

Figure 8-2: Example culvert hydraulic performance curve (Connecticut DOT, 2014).

performance of their culverts using updated precipitation data for the State and considering potential increases in precipitation in the future (see example analysis in Figure 8.2). This case study demonstrates the value of (1) regularly updating historical weather and discharge data, (2) investigating changes in environmental trends and projections and (3) analyzing how changes in environmental trends could affect the performance of assets. The State found that 18 of the 52 structures tested (35 percent) would not satisfy current hydraulic design criteria using updated precipitation estimates and were therefore hydraulically inadequate compared to recent design practices. Four of these structures would have been considered hydraulically adequate using earlier precipitation data from NOAA's 1961 Technical Paper 40 (Hershfield, 1961); many of the structures were designed before this data was available.

Pavement management systems

For pavements, States generally do not estimate or consider deterioration caused by environmental conditions such as extreme weather events. Currently, pavement deterioration models are typically developed based on historical condition as observed by measuring attributes such as ride quality, rutting, cracking, raveling, and other distresses. Separate deterioration models are often developed to predict vehicle load related condition impacts and non-load or "environmental" related impacts. The approaches used to develop deterioration models often vary from State to State where different factors are considered such as soil types, layer thicknesses, material types, traffic type and amount, and environmental climate zones.

Figure 8-3. Example of pavement deterioration (NJDOT, 2019).

Typically, States vary deterioration models based on factors such as road classification and traffic levels; some States may use management systems that include environmental factors that vary at a regional level to reflect different climates (i.e., hot versus cold areas). Many States have a family of deterioration curves that they use to predict pavement deterioration. These deterioration models are assigned to specific subsets of the network. How these sub-networks are selected varies from State to State. For example, the deterioration model for minor arterials in one State may be different from the deterioration model for major arterials. Each of these deterioration models could cover hundreds of miles of roads. Extreme weather events are generally localized and could impact one or several sub-networks.

Kentucky: integrating extreme heat into the pavement management system

Kentucky Transportation Cabinet (KYTC) demonstrated the viability of using future temperature projections as an input for pavement design and performance modeling. Specifically, KYTC used AASHTOWare® Pavement ME Design, a performance prediction tool that predicts the performance of a pavement structure over time, given specific design characteristics, traffic loadings, and environmental conditions.

KYTC used Pavement ME to predict pavement performance for both a 20-year and 40-year anticipated pavement life under historical temperatures and projected future increases in temperatures. The model predicted an increase in pavement rutting and fatigue cracking as a result of the warmer future environmental condition scenario. However, these increases were within the acceptable range of pavement performance and were not high enough to warrant altering the pavement design to withstand the hotter conditions.

See the Appendix or page 29 of the KYTC Asset Management, Extreme Weather, and Proxy Indicators pilot for more information (Kentucky Transportation Cabinet, 2019).

Texas: integrating flooding into the pavement management system

Texas DOT (TxDOT) assessed flood risk to pavements based on the probability of a flood event occurring and an estimate of damage. TxDOT simulated the impact of flooding on the structural capacity of selected pavement structures using TxME pavement design software. The team simulated different scenarios of traffic levels, pavement structures, and flooding events (regular flood events that occur within delineated floodways, as well as the 100-year and 500-year flood events) to assess the effects of flooding on the service life of flexible pavements.

The pavement analysis found that thinner pavement structures, particularly those without treated subgrades and less than two inches of asphalt, are particularly vulnerable to damage from flooding and may need to be hardened post flood event. If thinner pavement sections are heavily trafficked during flood response, immediate pavement damage can be expected that will likely require immediate reconstruction.

See the Appendix or page 46 of TxDOT Asset Management, Extreme Weather, and Proxy Indicators pilot for more information (TxDOT, 2019).

For example, one flood event may impact 10 to 15 miles of roads within a sub-network that is 500 miles long, or extreme heat may be a threat to only a specific region of a State with a network that consists of thousands of miles of roads. As a result, making changes to a deterioration model that covers an entire network or sub-network is not practical because only a fraction of the system is exposed to an extreme event. In these cases, it may be more practical to create a smaller network covering the roads that are exposed to the recurring natural hazard and then investigate the best possible methodology to forecast how pavements may deteriorate, as discussed in *Section 4.1: Establish hazard categories to reflect vulnerability to environmental conditions*. Consider any new studies and keep in mind that some environmental conditions may have little impact on deterioration. Some natural hazards may only cause damage and should be addressed during design stages and through the risk management plan (see *Chapter 7: Establish Risk Management Process*). In some cases, the best option may be to increase the frequency of maintenance and to monitor the impact of recurring events before a decision is made to adjust the life-cycle plan.

Additional approaches to improving the forecasting of environmental condition impacts on pavement degradation include:

- Collect data on asset condition and climate-related performance by environmental zones. Agencies could use the *Mechanistic-Empirical Pavement Design Guide* (historic) climate data as a starting point.
- Apply environmental zones to deterioration models similar to bridge management systems.

Maryland: integrating pavement flooding into a pavement management system

State life cycle plans will evolve overtime as asset management practices mature. Mature practices tie to more advanced tools capable of performing risk-based analyses. Today, some management systems allow classification of assets within several environmental categories. However, the ability to incorporate environmental hazards, such as increases in temperature or more frequent intense rainfall, into management system analyses is not yet well established for many agencies. Some advanced efforts are under way. For example, **MDOT SHA** is improving its pavement management given the threat it faces from sea level rise and extreme weather.

- MDOT SHA is calculating the percentage of time different roadway sections are projected to be inundated in the future and is capturing inundation to inform its pavement modeling.
- It is adding a field to its pavement inventory to capture the frequency of inundation of sections, again to improve modeling, materials selection, pavement design, and life cycle planning.
- It also is updating the model to reflect current and expected inundation frequency. Not only should that improve modeling, it also is expected to influence investments in maintenance.

8.3 Utilize Evaluations of Repeatedly Damaged Assets in Life-Cycle Planning

Each State DOT must conduct statewide evaluations to determine if there are reasonable alternatives to roads, highways, and bridges that have required repair and reconstruction activities on two or more occasions due to emergency events (23 CFR 667.1).[4] The required evaluation includes all impacted assets extending back to January 1, 1997 (23 CFR 667.5(a)). The results provide useful information to agencies as they consider life-cycle plans regarding future asset treatments. This consideration can increase the ability of an asset to be more resilient than it would have been otherwise based on previous asset performance.

8.4 Develop Mitigation Strategies for Life-Cycle Planning

Life-cycle planning strategies are well suited for addressing gradual ongoing risks from sea level rise, changing precipitation patterns, or increasing average temperatures. To successfully incorporate these issues into life-cycle planning, consider collecting data to discern the effects of environmental change and extremes on asset condition. As agency knowledge increases, consider updating policies and the way design standards are applied (i.e., if the design standard is a 25-year flow for a particular facility, assess how the 25-year flow is expected to change for the facility in question and also use these updated flows for future designs). Additional updates could include specifications for materials and treatment techniques. Agencies may choose to apply those standards to new construction as well as reconstruction and rehabilitation. Life-cycle strategies may cascade through all areas of an agency, from the front-line maintenance crews to staff focused on long-term planning. The need to manage assets effectively over their life-cycle involves coordination and collaboration across many work units to ensure that the full impact of severe weather is addressed. Establishing protocols – for maintenance, preservation, rehabilitation and

Importance of Asset Design Strategies

Strategies related to the initial construction and design of assets are often most effective for increasing resilience and extending the service life of assets. An agency's asset management team should work with project planners and engineers to identify appropriate design or reconstruction strategies.

For example, an agency could modify how it applies design standards to account for future conditions (e.g., using projected storm surge and flood conditions to determine the appropriate height of a bridge to withstand future conditions).

Refer to FHWA's Synthesis of Approaches for Addressing Resilience in Project Development for information on the steps and approaches to integrating resilience into design.

[4] Reasonable alternative is defined in 23 CFR Part 667.3 as:

Reasonable alternatives include options that could partially or fully achieve the following:
(1) Reduce the need for Federal funds to be expended on emergency repair and reconstruction activities;
(2) Better protect public safety and health and the human and natural environment; and
(3) Meet transportation needs as described in the relevant and applicable Federal, State, local, and tribal plans and programs. Relevant and applicable plans and programs include the Long-Range Statewide Transportation Plan, Statewide Transportation Improvement Plan (STIP), Metropolitan Transportation Plan(s), and Transportation Improvement Program(s) (TIP) that are developed under part 450 of this title.

replacement, and generally for evaluating resilience investment needs – can help with this coordination.

Be flexible in deciding how to repair damaged assets to enable them to function as intended now and in the future. Before making investments, it is useful to assess the potential long-term climate change impacts. Annualize the potential agency (and user) costs of these risks, the reduction in annualized cost if mitigation is performed, and the costs of mitigation to make asset classes and sub-groups more resilient. Agencies can then use this information to conduct economic analyses that cover the full life-cycle to inform investment decisions.

To develop life-cycle planning strategies that address gradually changing environmental conditions and their impacts on asset deterioration, transportation agencies will benefit from a strong monitoring plan to search for trends in deterioration that develop over longer periods of time and to reveal slow shifts in these weather-related deterioration measures (see *Chapter 10: Develop a Monitoring Plan to Track Risks Related to Extreme Weather and Climate Change*). When appropriate, and based on monitoring efforts, agencies can instigate a strategic change in materials and design. However, this by itself will likely be insufficient for addressing extreme weather events. Agencies will likely need to assess future environmental conditions; consider their effects on asset performance; and develop life-cycle planning strategies to address them.

Preventive maintenance is another key life-cycle strategy to address deterioration issues associated with climate change. Examples of potential maintenance strategies include:

- Conduct regular drainage maintenance to reduce flooding risks and extend the service life of assets (see text box below for more information).
- Conduct regular maintenance of overhead signs and high-mast towers to tighten base bolts and inspect for cracks to increase their resilience to high wind.

- Regularly remove debris and make repairs as necessary to bridge piers, abutments, scour and erosion-protection systems, and wingwalls to decrease the potential for damage and increase resilience to flooding.

Importance of Drainage Maintenance

Drainage maintenance is very important to extending the service life of vulnerable assets. Vegetation, soil, debris, and erosion can cause drainage assets to perform poorly and fail to convey water away from roadways after events (FHWA, 2015a). Over time the lack of effective drainage can degrade water quality, degrade pavement performance, and increase the frequency or duration of flooding.

The importance of systematic programs to maintain drainage may increase as storm severity increases and as coastal sea levels rise. Maintenance activities could include:

- Clearing debris from inlets and pipes to prevent failure.
- Re-grading ditches and swales to maintain adequate gradients to drain water.
- Elevating or relocating outfalls to maintain effective drainage and prevent the outfall from being inundated by flood waters or sea level rise.
- Reporting tidally influenced drainage that is underwater and inaccessible to maintenance for discussion of engineering solutions.

Lastly, operational changes can limit the impacts of extreme weather and changing environmental conditions on asset deterioration. For example, DOTs in cold regions can institute spring weight restrictions to protect roadways from accelerated deterioration as the frozen winter ground thaws.

Good pavement and bridge maintenance records are essential to developing accurate deterioration curves and forecasts. It is common in bridge and pavement inventories for pavement or bridge conditions to improve but there is no record of why. Often, some unrecorded maintenance activity occurs that does not appear in the inventory. Without a methodology for capturing maintenance activities, the process of documenting how maintenance influences asset condition involves manually reviewing work orders. This lack of integrated data prevents calculating the actual performance of assets, the cost of poor performing assets, and hinders understanding how the asset actually performs.

8.5 Recap of Integrating Resilience into Life-Cycle Planning

Life-cycle planning lies at the heart of asset management. Key to the long-term, economic performance of assets is a structured sequence of initial construction, maintenance, preservation, rehabilitation, and reconstruction applied at the appropriate points in an asset's life-cycle. How assets perform over their life-cycle is directly affected by environmental conditions that will be subjecting them to increasingly severe changes in temperature and precipitation. To keep life-cycle processes ahead of changing environmental conditions, agencies need to understand how changes in precipitation and temperature affect long-term asset performance. Agencies should identify asset classes and sub-groups of classes that are most vulnerable to extremes, or to changes in frequency of hazards, deterioration, and/or service disruption (such as frequency of overtopping, number of freeze/thaw events, wet days, and other factors that affect how their life-cycle strategies need to evolve). Before investing in an asset today, understand if the asset is potentially affected by changing environmental conditions over the long term. Agencies can use Table 8-1 to check off actions they have already taken to integrate resilience to extreme weather events and climate change into transportation asset management and prioritize remaining actions.

Consider including in the TAMP Life Cycle Plan: Life cycle planning strategies that address ongoing changes in current and future environmental conditions

Agencies can describe the new actions they will take to integrate resilience to future environmental conditions into life cycle decisions, and can utilize the 23 CFR Part 667 evaluation results to identify assets particularly prone to damage from extreme events.

Table 8-1. Checklist of Potential Actions on Integrating Resilience into Life-cycle Planning for Transportation Asset Management

Complete?	What to analyze?	What to include?
	To integrate future environmental conditions and weather-related risks into the life-cycle planning process: • Assess how future weather patterns could affect asset deterioration and treatment effectiveness, and influence decisions to invest in assets or abandon/relocate them. • Integrate extreme weather events and climate change into bridges, culvert, and pavement management systems and other analytical tools. • Utilize evaluations of repeatedly damaged assets to identify those particularly prone to damage from extreme weather events. • Conduct tradeoff analyses to determine if mitigation is appropriate or cost effective. • Determine how environmental conditions may change over the life of the asset. • When analyzing and deciding on project work types (initial construction, maintenance, preservation, rehabilitation, reconstruction), consider the effects of extreme events and climate change on the long-term sustainability and use of the asset, and the cost effectiveness of the proposed work type or needed adaptation options.	• Specify how gradual changes in environmental conditions may affect asset deterioration and associated maintenance/treatment needs. • Include mitigation strategies to integrate resilience to gradual changes in future environmental conditions into life-cycle decisions. • Reinforce the emphasis upon good maintenance practices as a means to extend asset life and improve asset resilience. • Track level of maintenance required for normal operation and for extreme events

9 ESTABLISH RESILIENT INVESTMENT STRATEGIES AND FINANCIAL PLANS

Financial plan and investment strategy development are closely linked, concurrent and iterative activities. Financial plans are the means by which an agency can allocate resources to the investment strategies that have been fine-tuned to achieve asset management objectives. Investment strategies can then translate the analysis conducted throughout the asset management process into decisions on what to invest in and at what level.

Decisions of how much to invest are often influenced by the agency's objectives, the gap analysis, risk analysis, and its life-cycle planning. As Figure 9-1 indicates, at a macro level the costs resulting from weather and climate disasters in the U.S. (including but not limited to transportation) are likely to rise. As transportation agencies develop asset management financial plans, these plans will likely need to accommodate more frequent weather-related damages.

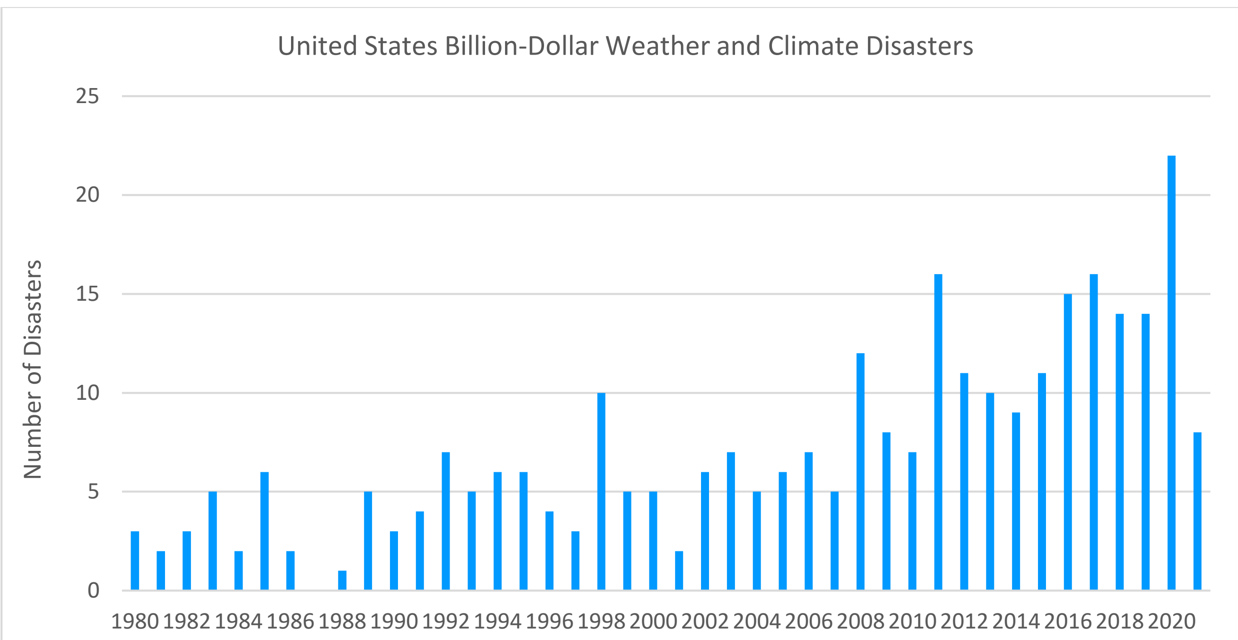

Figure 9-1. Billion-dollar weather and climate disasters in the US have increased from 1980 to 2017 (NCEI, 2019).

A financial plan forecasts the agency's revenues and expenditures and explains how the revenues will be allocated to achieve the investment strategies. The financial plan includes the estimated funding levels that are reasonably expected to be available, by fiscal year, to address the costs of future projects. Decisions on what types of projects should receive funding for different types of asset management resilience efforts are made as part of the investment strategy development. As alternative asset management and resilience strategies are evaluated, an agency may evaluate different ways to allocate resources among assets, strategies, and work types.

A useful format for investment strategies is to identify a set of funding programs tied to the achievement of specific objectives or targets and work types which include initial construction, maintenance, preservation, rehabilitation, and reconstruction. Note that any action taken to address resilience could still fit under one of the categories included in asset management plan work types. This is why including resilience in asset management objectives, measures and targets is so important (see *Chapter 6: Set Resilience Objectives, Measures and Targets*). Multi-objective analysis can support decision making when making tradeoffs between funding levels, asset conditions, asset performance, and risk. Then, 10 years of projected funding levels can be shown for the programs. In their entirety, investment strategies may include both narrative explanation of the funding program and its intent, and a 10-year table of funding allocations for the program.

The investment strategies can be the place where an agency indicates how it funds specific programs to reduce the risk of damages resulting from extreme weather events or increased deterioration resulting from climate change, and how it enhances existing programs to do so. For example, an agency could include separate line items for programs to stabilize denuded hillsides, mitigate bridge flooding risk, enhance at-risk drainage, or mitigate coastal bridges to protect them from sea level rise and storm surge. Or, if separate programs are not funded for those activities, an agency could indicate how it has incorporated those strategies into existing programs, such as for bridges, pavements, or maintenance.

What is a financial plan?

A "financial plan" in the context of this report means a long-term plan spanning 10 years or longer, presenting a State DOT's estimate of projected available financial resources and predicted expenditures in major asset categories that can be used to achieve State DOT targets for asset condition during the plan period, and highlighting how resources are expected to be allocated based on asset strategies, needs, shortfalls, and agency policies. As noted in 23 CFR 515.5:

(d) A State DOT shall establish a process for the development of a financial plan that identifies annual costs over a minimum period of 10 years. The financial plan process shall, at a minimum, produce:

(1) The estimated cost of expected future work to implement investment strategies contained in the asset management plan, by State fiscal year and work type;

(2) The estimated funding levels that are expected to be reasonably available, by fiscal year, to address the costs of future work types. State DOTs may estimate the amount of available future funding using historical values where the future funding amount is uncertain;

(3) Identification of anticipated funding sources; and

(4) An estimate of the value of the agency's NHS pavement and bridge assets and the needed investment on an annual basis to maintain the value of these assets. 23 CFR 515.7(d)

9.1 Consider no-risk, incremental investment decisions

The uncertainty surrounding long-term impacts of future environmental conditions and the effects of more intense but less-predictable weather events further compounds the complexity of developing long-term investment strategies. This uncertainty increases the value in investing in "no regrets" or low to no-risk strategies in the short-term, while developing adaptive or incremental plans for longer term investment decisions. "Adaptive management" strategies can include designing assets to facilitate retrofits later when the timing and intensity of future conditions and responses of assets to those conditions become clearer.

Uncertainty in the timing of extreme weather events

Forecasting basic investment strategy inputs such as material costs and future inflation rates already present major challenges. Predicting the rate of change in material prices creates substantial uncertainty when transportation agencies are developing 10-year, or longer, investment strategies. The substantial variability seen in just one such factor, diesel fuel prices in Figure 9-2, illustrates the complexity.

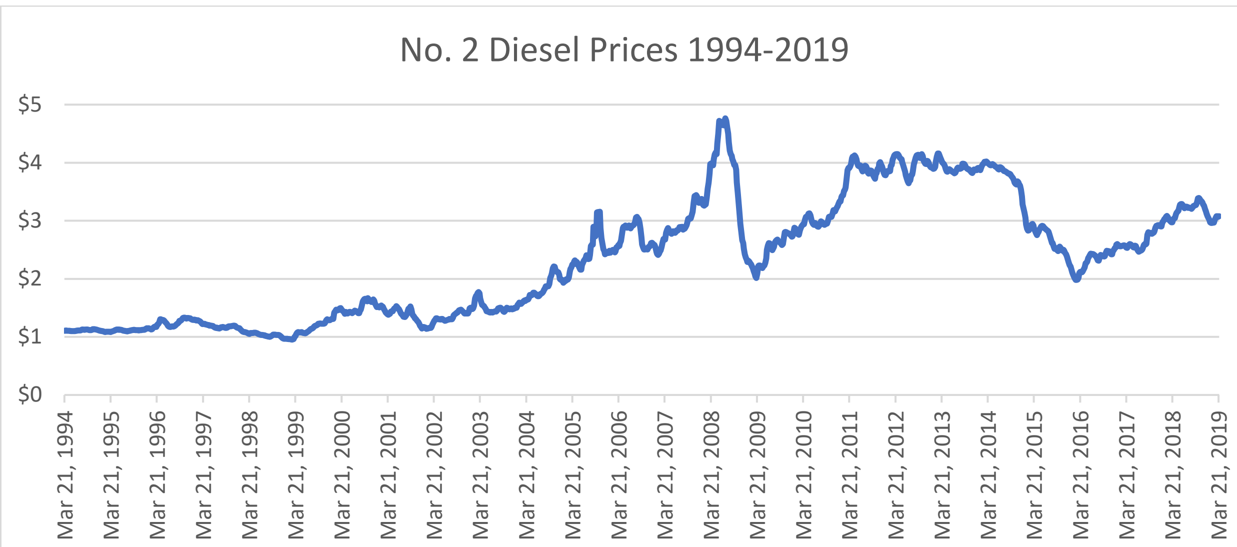

Figure 9-2. Erratic change in a major cost estimating factor, diesel fuel prices 1994–2019. (Energy Information Administration, 2019)

Similarly, the timing of extreme weather events is very difficult to forecast. While we can estimate the return period - or, the likelihood of experiencing a particular level of event over a period of time - of various extreme weather events such as heavy rainfall events, we cannot determine in which year they will occur. For example, Figure 9-3 demonstrates the increases in extreme one-day precipitation events as reported by the U.S. Environmental Protection Agency. Although we cannot predict the precise timing of extreme weather events at a specific location, the overall trend of increasing events is well documented. (See USGCRP 2018, Chapter 2) Because these trends are increasing, they become an important consideration in the long timeframes of managing assets over their entire service life.

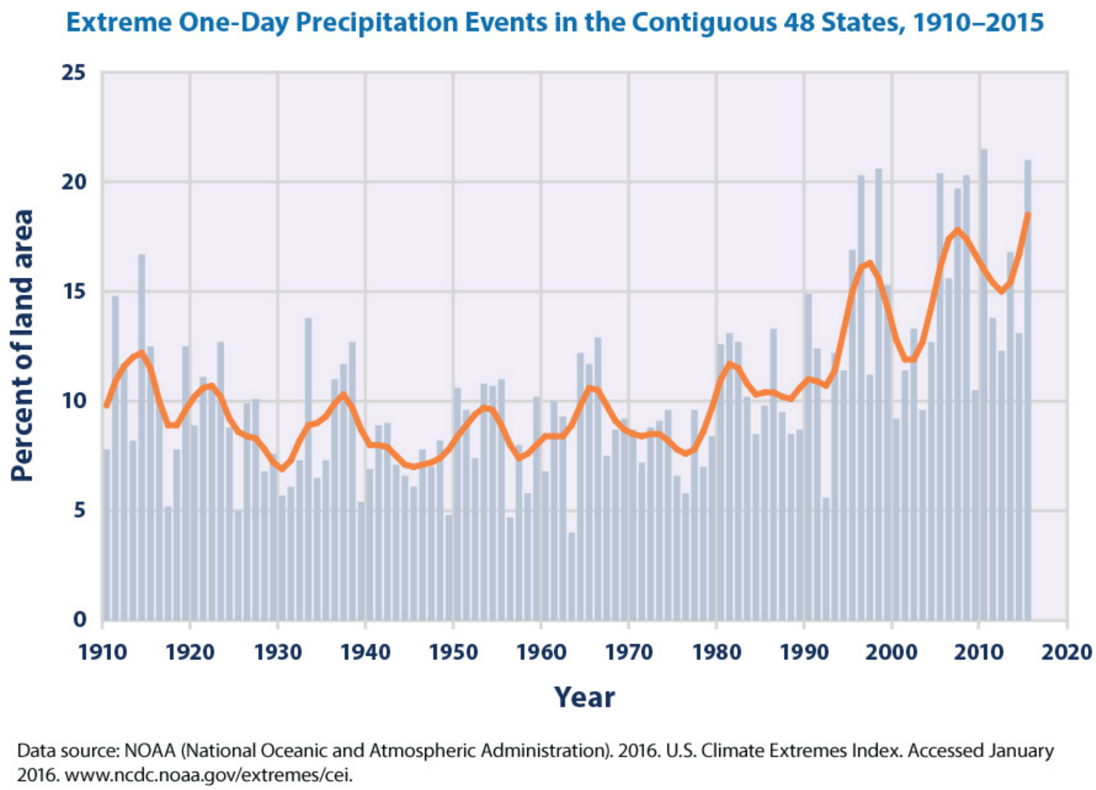

Figure 9-3: Extreme one-day precipitation events (EPA, 2016).

As discussed in *Chapter 8: Develop Life-cycle Plan* and *Section 3.2: How are the hazards changing?*, although an asset management plan may have a 10-year horizon, transportation agencies manage assets over much longer time periods; investment plans over the 10-year period should be made while considering longer term strategies in line with the life span of bridges and pavement systems. Assets such as major structures may have life-cycles of 75 or 100 years, while many Interstate pavements may retain their base and base courses for 40 or 50 years. Over these longer time frames, the likelihood of an asset experiencing an extreme weather event significantly increases. Therefore, it is important to consider potential investments 20 to 40 years (minimum) into the future to better reflect the range of needed investments over the life-cycle of the different asset classes and subgroups. See *Section 3.2: How are the hazards changing?* for more information on how to define asset management timeframes as they relate to environmental conditions and risks and where to obtain projections of changing environmental conditions.

Uncertainty in projections of future environmental conditions

Added to the existing forecasting complexity is the potential influence of climate change. For example, hurricanes of a greater intensity, higher temperatures, sea-level rise, changes in seasonal precipitation and higher intensity heavy rain events are expected, but forecasters generally lack the ability to indicate when and where they will occur (USGCRP, 2018). Uncertainty around climate change includes:

- **Scientific or model uncertainty:** Models of climate do not perfectly capture all natural processes because of the limits of scientists' understanding of natural processes and because models are not able to numerically capture all global climate processes.
- **Scenario or human uncertainty:** Around the globe, people and governments are acting to reduce greenhouse gas emissions, but how much they will succeed is uncertain.
- **Natural variability:** As discussed above, climate and weather have natural variations year to year, and any single year may not be representative of overall trends.

These uncertainties mean that future environmental conditions are expressed as a range of possible futures, such as the range in future sea levels included in Figure 9-4. The three types of uncertainty and approaches to addressing them are covered in more detail in Chapter 4 of FHWA's *Synthesis of Approaches for Addressing Resilience in Project Development*.

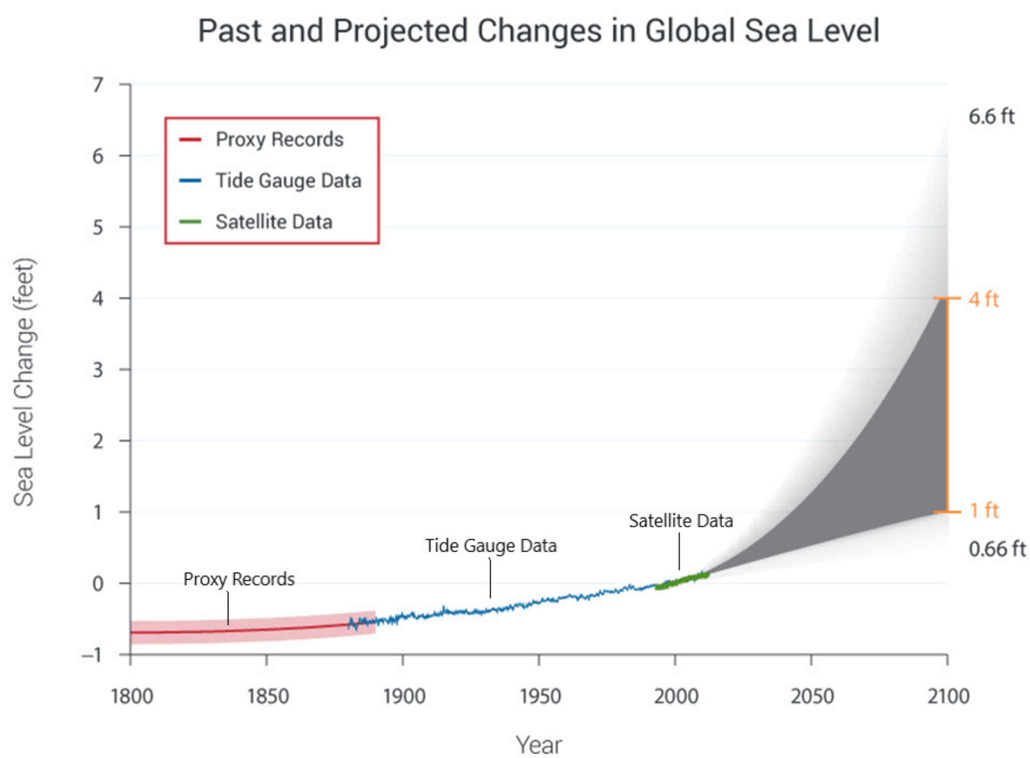

Figure 9-4: Uncertainty in sea level rise projections increases over time (Walsh, 2014; Parris, 2012).

To address the long-term uncertainty, agencies may elect to:

- Plan for frequent updates to strategies, perhaps on an annual or biennial basis.
- Increase the monitoring of environmental conditions such as average mean temperature, rainfall variability, fire frequency, or sea level rise and storm intensity.
- Adopt adaptive management plans or incremental strategies such as the staged culvert-expansion strategy employed by the **Colorado DOT**, which identified culverts that may be at greater risk if adjacent slopes are denuded by fire (see *Section 7.4: Develop risk mitigation strategies*).

- Adopt “no regrets” strategies such as providing inventory data for at-risk assets and updating forecasts of long-term weather trends to reflect climate projections.

9.2 Identify Possible Investment Strategies for Subsets of Assets Vulnerable to Weather-Related Risks

Transportation agencies may want to specify investment strategies and program amounts to address impacts from current and future environmental conditions. Agencies can also monitor risks over time (see *Chapter 10: Develop a Monitoring Plan to Track Risks Related to Extreme Weather and Climate Change*) until the level of risk triggers the need for investment strategies and programs. Programs to mitigate risks from gradually occurring hazards such as erosion or sea level rise are the types of long-term investments suitable for investment strategies. For example, these programs could use a combination of engineered and nature-based solutions to both stabilize the coastal area and dissipate wave impacts.

It is also important to reflect variability in investment strategies. A variety of weather-related impacts could influence material selection, application of design standards, and the amounts allocated to investment strategies. For example, paving frequencies may need to be increased or pavement mixes changed if higher future temperatures are expected to increase rutting or soil expansion and contraction. Coastal-stabilization programs may need increased attention and funding, as may drainage programs to cope with increased storm intensities.

Agencies can use investment strategies to elaborate on how bridge and pavement programs have been enhanced to minimize, or at least monitor, the risks to them, as identified in *Chapter 7: Establish Risk Management Process*. The initial transportation asset management plans included several examples of specific programs to address weather or environmental-related risks (Table 9-1).

Table 9-1. Examples of Resilience Investment Strategies

Resilient Investment Strategy	Asset Type	Risk/ Vulnerability Addressed	Example
Increase roadside infrastructure budgets	Stormwater tunnels; culverts; other hydraulic assets	Flooding	**Minnesota DOT** (MnDOT)’s initial asset management plan identified deep stormwater tunnels as well as its culverts and other hydraulic assets as high risks. The culverts comprise the majority of the $700 million devoted to its Roadside Infrastructure program through 2027 (MnDOT, 2018).
Increase operations and	Drainage assets	Flooding	The **MnDOT** TAMP indicates that operations and maintenance will spend about $10 million annually for drainage maintenance, with $4.5 million needed for deep stormwater tunnels (MnDOT, 2018).

Resilient Investment Strategy	Asset Type	Risk/ Vulnerability Addressed	Example
maintenance budgets	Drainage system	Sea level rise and storm surge	The **Rhode Island DOT** initial TAMP includes specific strategies and line items for stormwater maintenance and improvement. Although the program was started because of an environmental consent decree and not as a weather-risk mitigation, the program will consider sea level rise and storm surge improvements when addressing highway network drainage. The investment strategies allocate $72 million over 10 years for drainage capital improvements and $60.6 million for maintenance. Maintenance includes cleaning, flushing, removing sediment, and other routine maintenance to keep the system functional (RIDOT, 2018).
Develop standalone risk mitigation investment strategy	Bridges	n/a	Although not related to weather, a risk-driven analogous funding program is the **Washington State DOT's** bridge seismic risk program. WSDOT identifies seismic risks separately from bridge-condition needs (WSDOT, 2018a). WSDOT has invested nearly $150 million since 1991 to strengthen its lifeline bridges. Approximately 1,600 retrofits are either completed or nearly so. If structures are not appropriate for retrofit, they are scheduled for replacement (WSDOT, 2015).
Include risk mitigation in rehabilitation budgets	Bridges	n/a	**Oregon DOT** amended its bridge rehabilitation program to incorporate a risk-based approach to seismic resilience. It conducted a study of its seismic vulnerabilities and noted that a majority of its bridges were built between 1950 and 1980 before many seismic standards were in place (Nako, Shike, Six, Johnson, & Dusicka, 2009). Of the 2,550 structures examined, 1,670 were found to have insufficient capacity to resist earthquake loadings. The high cost of retrofitting so many structures was beyond the agency's budget, so it pursued less costly options. The agency applied a portion of the existing bridge budget to retrofit some of the longer sections of highway to ensure mobility for greater areas if an earthquake did occur. The agency also established a design policy to include at least a Phase I seismic retrofit to vulnerable bridges that are scheduled for rehabilitation, which involves preventing the superstructure from separating from the substructure. Including the Phase I elements with bridge rehabilitation projects has been cost effective by reducing design and mobilization costs.

Resilient Investment Strategy	Asset Type	Risk/ Vulnerability Addressed	Example
Dedicate funding for slope remediation program	Roads	Erosion	The **WSDOT** Unstable Slope Management Program began in 1995 with an initial assessment of 2,500 sites, since growing to 3,400 sites. Sites are rated with the lowest possible score of 33 and highest possible at 891 (WSDOT, 2018b). WSDOT prioritizes remediation for sites with scores above 300 or greater along Interstate Highways or other facilities with an excess of 1,000 vehicles per day, if the remediation has a benefit/cost ratio of at least 1. Currently, the program is funded at $51 million over eight years, with an estimate that $30 million would be needed annually to mitigate all identified unstable slopes.
Consider nature-based solutions	Roads	Coastal erosion	**Maine DOT** examined a set of nature-based solutions to stabilize a section of Route 209 while respecting its environmental sensitivity. It estimated that for an annualized cost of $191,622 per year it could protect the road without having to use a "grey" alternative such as riprap or sheet piling for 64 years (FHWA, Maine DOT, New Hampshire DOT, 2018). If similar strategies are adopted elsewhere, their funding could become a common element of maintenance programs. The ongoing maintenance of these nature-based solutions could mitigate the impacts of extreme weather or changing climate and become as common as roadway vegetation management programs are today.

Storm Surge and Sea Level Rise Investment Considerations

There are more than 70,000 bridges crossing coastal, tidally-influenced waters in the United States (FHWA, 2016b). In recent years, billions of dollars have been spent rebuilding bridges damaged by storm surge along the Gulf Coast alone (FHWA 2016). In the future, sea level rise will further increase storm surge elevations and increase the vulnerability of many existing bridges to waves on storm surge (FHWA, 2016b).

An FHWA-sponsored study of one representative bridge indicated that it was built to withstand both dead and live loads but not the upward or lateral loads caused by a major hurricane storm surge. The study concluded that retrofit and bridge-elevating strategies were needed to make this structure resilient. The study recommended that a facility management plan be developed for the at-risk structure, which could provide estimates of the long-term investment strategies necessary to keep the bridge in service (FHWA 2016b). Long-term programs to make coastal structures “high and dry or low and strong” could be the type of investment strategy that would complement risk-based asset management plans.

Although programs to systematically elevate or relocate transportation assets vulnerable to sea level rise and storm surge are complex, expensive, and in their infancy, they are likely to become more significant influences upon investment strategies over time. When the full life cycle cost of a facility is considered, elevating or relocating the facility could be a cost-effective solution. Because of the high cost, and the evolving risk, programs to elevate and relocate assets lend themselves to the type of long-term investment strategy included in an asset management or long-range plan. The Climate Adaptation Knowledge Exchange has several examples and case studies relating to the managed retreat of built infrastructure for more information.

Consider including in the TAMP Investment Strategy: Identify possible investment strategies for vulnerable assets

Identify the strategies to be used for categories of assets at risk to weather-related risks. Each category of assets may have a separate investment strategy.

9.3 Integrate Resilience into Financial Plans

The financial plan is where agencies assign capital and operating resources to achieve objectives and mitigate risks and vulnerabilities. Therefore, this component plays a critical role in the implementation of an agency’s risk mitigation strategies. Potential opportunities to integrate resilience are detailed below.

Track expenditures caused by extreme weather over time

A useful first step in financial planning is to conduct an analysis of outlays for past emergencies, even if the emergencies are not large enough to trigger a disaster declaration. Nearly all budgeting is incremental and based upon historical trends. Typically, past revenue and expenditure trends are examined and used as the basis for a modified forecast of future revenue expectations and planned expenditures. An examination of past emergency trends can indicate the extent to which the number and magnitude of emergencies have changed and how frequently they occurred in the past. If an individual State's historical trends are increasing, the agency may expect that its future revenues and expenditures also will be increasingly affected by emergency events.

Develop contingency funds for addressing extreme weather events exacerbated by climate change

Financial planners can develop contingencies and scenarios for extreme weather events that can be deployed should emergencies become increasingly common. "Rainy day" accounts to help pay for emergencies are not typically possible for two reasons: agencies often lack the resources to develop such accounts and appropriation processes do not usually allow for them. Legislatures usually reallocate unspent amounts. However, there are alternative ways to develop scenarios that are functionally similar to rainy day funds.

For example, an agency can wait to use a bond appropriation that can be issued if there is a major emergency. Withholding bond capacity can be a no-regrets financial strategy because the bonds are not issued unless they are needed, and the agency does not otherwise incur underwriting or interest costs. Another way to plan for a virtual rainy-day fund is to identify major reconstruction projects that can be delayed or rescoped to lesser scopes and their funding re-allocated for the emergencies. Agencies often have major bridge or pavement replacements under development when life-cycle analysis justifies full replacement. However, in an emergency, they can be postponed and treated with lesser scopes to buy the agency several years of additional life. Although this is not the optimum life-cycle strategy for the major asset, the greater overall network need may warrant the re-prioritization of an individual asset.

Financial Scenario Planning

Scenario planning is common in most emergency-response organizations. It also could be possible in planning for emergencies that could impact asset management financial plans. Financial-response scenarios that could be identified and planned for include:

- Determining how to quickly re-prioritize projects and programs if unexpected inflation caused by emergency events impacts funding levels
- Deciding whether an additional bond issuance is possible to cover higher program costs
- Preparing for emergency legislative appropriations to cover additional expenses

Develop cost-inflation factors to apply to large-scale recovery

Consider developing cost-inflation factors to apply to large-scale recovery programs to enhance financial planning. Unit cost estimates are based on past bids, which usually are offered under normal market conditions. During emergencies there may be a spike in the number of projects along with a scarcity of materials, equipment, contractors, and skilled labor, all of which drive up unit costs. The cost estimation for emergencies could be enhanced by factoring these influences into the estimating process and by having such estimating factors at hand in advance of emergencies.

Prepare for lingering failures after extreme weather events

Lingering failures following extreme weather events can be costly. Therefore, it is important that agencies prepare for the potential of failures. An analysis of the effects of Hurricane Sandy on New York, New Jersey, and Connecticut found that post-storm impacts may not become apparent for years afterwards (FHWA, 2017c). Rail signals in New York failed repeatedly in the months after Sandy with outages attributed to saltwater corrosion of the electrical and mechanical systems. A year after Sandy, an escalator failed on the PATH subway in New Jersey. Repairs indicated that the station was damaged by saltwater from storm surge inundation. As of 2020, the MTA New York City Transit L Train still requires extensive repairs to address damage caused by the inundation.

Fund resilience improvements for important subsets of assets

The financial plan can incorporate specific funding for resilience programs, including capital programs as well as enhanced maintenance programs. These can become among the "off the top" programs that strongly influence financial plans. The amount of revenue available to distribute to bridges and pavements is usually influenced by how much revenue is devoted to costs such as debt service, operating expenses, and required pass-throughs such as to local governments. As resilience becomes more critical, programs that support it may become specific line items that influence the investment strategies and financial plans. Examples could include programs for slope stabilization, upgrading of hydraulic structures, or elevating coastal assets. Agency examples include:

- **New York State DOT (NYSDOT)** initiated a Critical Bridges Over Water Program to harden 106 at-risk bridges against extreme weather, including flooding and, potentially, scour. By December 2016, NYSDOT had received funding approvals from FEMA for all of the bridges in the program, totaling $518 million (NYSDOT, 2019).
- **NYSDOT** also developed a Weather Hardening Program to mitigate destructive impacts of extreme weather to the state's infrastructure. The state provided $500 million in 2016 to make safe and passable roadways across the state that are susceptible to flooding and other extreme weather-related events, including ice jams (NYSDOT, 2019).
- **Rhode Island DOT** increased its drainage maintenance program. RIDOT forecasted costs for equipment, labor, materials, and project-development expenses for not only the startup of the program but for its increasing maintenance as retention and detention ponds were added across the state (RIDOT, 2018). There may be ongoing costs for equipment

to shape and contour ditches and swales but also specialty equipment such as vacuum trucks and sweepers to clean catch basins and drainage structures.

- **Colorado DOT (CDOT)** conducted a corridor risk and resilience pilot, which resulted in a number of recommendations to influence future investment strategies. One such recommendation to help fund resilience efforts was to allocate between 1% and 2.5% of the CDOT annual budget to risk and resilience efforts (AEM, 2017).

Transportation agencies may also want to consider budgeting for vulnerable assets that have not been included in the full asset management analysis such as culverts and geological assets that are highly vulnerable to extreme weather.

Identify costs and solutions for repeatedly damaged assets

Another investment strategy is to fund the strengthening of sites identified through statewide evaluations of roads and highways due to emergency events, including extreme weather. States can develop long-term mitigation strategies for locations identified through the 23 CFR Part 667 evaluation process and estimate the costs for those treatments. Those costs could be integrated into the long-term financial planning forecasts. Although the sites identified by the Part 667 evaluations may not be affected by projects in the current STIP, knowing what the costs are to make the Part 667 locations resilient can provide additional information to inform the financial plan development process.

Enhance emergency-recovery plans with resilience considerations

To prepare for future environmental conditions, consider enhancing emergency recovery plans. Although individual events may be unpredictable, most events involve reliable communication protocols, rapid damage assessment, flexible resource allocation, and prompt contracting. Having flexible response plans in place can allow an agency to be more responsive when the unexpected event strikes.

Recovery plans can include designing and contracting contingencies to respond and rebuild more quickly after an event occurs. These can include budgeting for contingency or emergency funds, having on-call design contracts, mutual-aid agreements, having detours pre-determined, and basic supplies stockpiled. Ensuring backup and redundant communication systems also can be important.

Conduct a Post-Disaster Analysis

Vermont Agency for Transportation (VTrans) conducted a post-disaster analysis following Hurricane Irene in 2011 (VTrans, 2012). It found that its contracting staffers were hindered by their lack of familiarity with FEMA and FHWA emergency documentation requirements. VTrans also found that it needed better lines of communication and the ability to process Detailed Damage Incident Reports more quickly. During such large events, additional staff often are called upon to handle the overwhelming short-term workload. VTrans identified training and communication steps it could take that could expedite accessing funds and authorizing contractors for future emergencies.

The recovery plan can include strategies for how to quickly replace assets so that they can withstand future events. Without a recovery plan, agencies are unlikely to consider resilience during the recovery process given the magnitude and urgency of needs at that time. By shifting the planning from after the disaster event to before (Figure 9-5), there is an opportunity when infrastructure is damaged to incorporate resilience measures into the repair or reconstruction of that asset. Agencies can likely decrease recovery time by providing as much detail as possible on the potential design of the resilience improvements. As such, disaster response plans could include relevant guidance and findings from studies such as vulnerability assessments and hazard mitigation plans. They also could include identified, but not funded, projects to increase asset resilience.

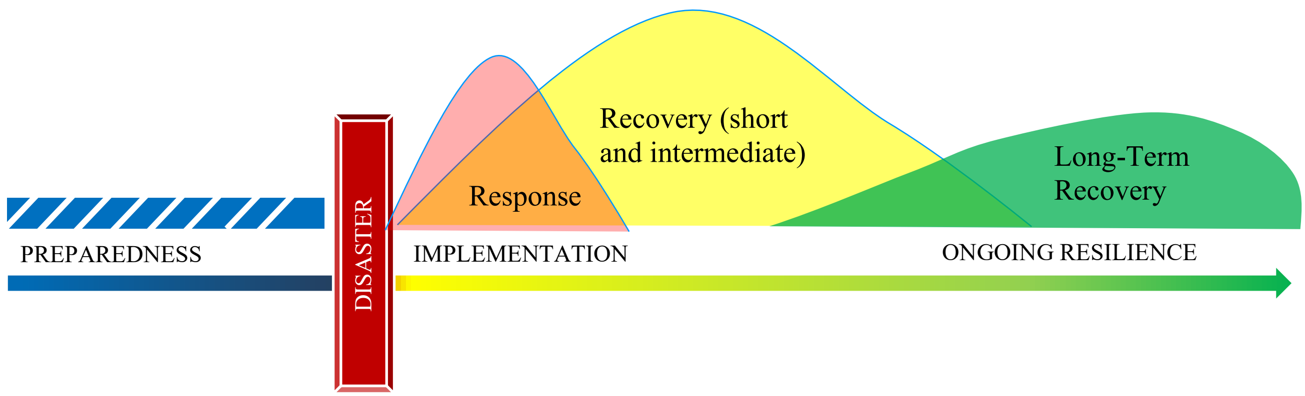

Figure 9-5. Disaster preparedness and response process. Source: ICF

Additional Resources on Disaster Preparedness Planning

- FHWA's Emergency Relief Manual was recently updated to allow for infrastructure damaged in extreme weather events to be repaired to a more resilient standard.
- FEMA's National Preparedness Goal outlines the capabilities and preliminary targets to consider when planning for recovery.
- FEMA's National Disaster Recovery Framework provides guidance to practitioners involved in the recovery process, including planning functions.
- NCHRP Report 753: A Pre-Event Recovery Planning Guide for Transportation is a comprehensive resource for transportation planners that includes checklists, tools, and resources to assist in the pre- and post-event recovery efforts.

Consider including in the TAMP Financial Plan: A strategy for proactively addressing resilience.

Describe the strategy for proactively addressing resilience for the assets in the TAMP through normal capital investment or dedicated funding streams. Include an estimated budget for additional maintenance required due to increases in the frequency or intensity of extreme weather events. Include an estimated budget to mitigate subgroups of assets in the TAMP that are highly vulnerable.

9.4 Recap of Integrating Resilience into Financial Plans and Investment Strategies

One of the hallmarks of a resilient agency is that it anticipates possible events and develops flexible strategies to deal with unexpected emergencies. Planning for resilience can extend to the asset management financial plan and investment strategy processes as well. Financial planners can examine the increasing rate and magnitude of emergencies and develop scenarios for how they may deal with emergencies in the future. They can develop contingency strategies for how they would re-prioritize outlays and anticipate how costs may be inflated by the construction peaks caused by response to widespread emergencies. They also can identify what new programs are essential and which will involve ongoing investments. Also, the financial team can anticipate and plan for the increased programming and need for rapid eligibility determinations that can accompany a major event. Just as maintenance and construction crews conduct scenarios of how to respond to future environmental impacts, so can the financial planning staff.

Transportation agency asset management financial plans and investment strategies can turn resilience planning into actionable programs. The long horizon and life-cycle focus of asset management plans should naturally encourage investment strategies that can reduce the threat of events during the entire life of an asset. When investments can lower agency and user life-cycle costs by improving the resilience of assets, they may present attractive investment strategies.

Agencies can enhance financial plans and investment strategies by:

- Identifying the specific assets and asset classes that may benefit from resilience treatments (as described in earlier chapters).
- Allocating funds to programs and to asset class subsets that are most at risk.
- Making immediate investments in those assets or preparing to reactively upgrade those assets if events occur.
- Funding and having ready quick-response plans to recover from a variety of events, even if individual events are impossible to predict.
- Having plans in place to conduct analyses on how to make damaged assets more resilient to withstand future events. Instead of only replacing in kind, agencies can have protocols in place to quickly analyze how to harden assets to withstand possible future events.

Table 9-2, can be used to check off actions an agency has already taken to integrate resilience to current and future environmental conditions and prioritize remaining actions.

Table 9-2. Checklist of Potential Actions on Integrating Resilience into Investment Strategies and the Financial Plan for Transportation Asset Management

Complete?	What to analyze?	What to include?
	What are the assets, asset classes, and strategies that should be funded to make the transportation system more resilient? • Identify at-risk assets • Develop strategies to fund their upgrade in the near term or be prepared to respond quickly to enhance them if damaged. • Fund 'all hazard' response plans • Develop design standards and strategies to address long-term threats.	Include investment strategies that respond to the long-term threats and which support mitigation activities to keep assets in a state of good repair and resilient to events.
	Develop strategies for incorporating resilience into the asset management financial process by: • Reviewing recent emergency event trends and anticipating how these trends could influence financial planning • Anticipating the funding needs for new resilience programs and how to sustain them Prepare for emergencies by conducting scenarios of how they may affect construction prices or create the need for rapid-response financial teams to process emergency authorizations.	Include a recognition that financial plans may need to be flexible to address future emergency events. Also, incorporate into the asset management financial planning process assets that support resilience

10 Develop a Monitoring Plan to Track Risks Related to Extreme Weather and Climate Change

If a transportation agency has integrated resilience considerations throughout the asset management process, it may be beneficial to track the effectiveness of those actions, and to monitor changes in environmental conditions to determine how risks are changing and if additional action should be taken. Risk mitigation efforts should be ongoing and continuous, as a part of the decision making process. Several avenues exist for monitoring and updating extreme weather mitigation strategies (FHWA, 2017f).

Monitoring Risks in the TAMP

Closely related to incorporating mitigation strategies into asset management is the monitoring of the success of the strategies. The asset management rule in 23 CFR Part 515 requires States to establish a process to identify and prioritize risks, a plan for addressing their top priority risks, and an approach for monitoring top priority risks (23 CFR 515.7(c)).

Regardless of how the agency organizes its implementation and monitoring efforts, what is most important is that the strategies become ingrained in the agency's asset management processes.

10.1 Track risk mitigation

As with most performance-based systems, feedback on strategy implementation and effectiveness is essential to performance management. Methods to track and monitor risks where mitigation strategies have been executed are identified below.

Use the risk register to monitor progress

The risk register can be used as a companion to a performance dashboard to monitor and apprise stakeholders of the status of the agency's risks and risk mitigation efforts. A dashboard illustrates performance objectives and status while a risk register illustrates the risks surrounding the performance and how they are managed. For example, Hampton Roads developed an online dashboard (Figure 10-1) to track and report the status of projects to increase resilience to sea level rise and coastal flooding in the area (Hampton Roads Planning District Commission, 2019). Risk registers can be updated on a regular cycle, such as quarterly or annually depending upon the timeline of the risk and its mitigation.

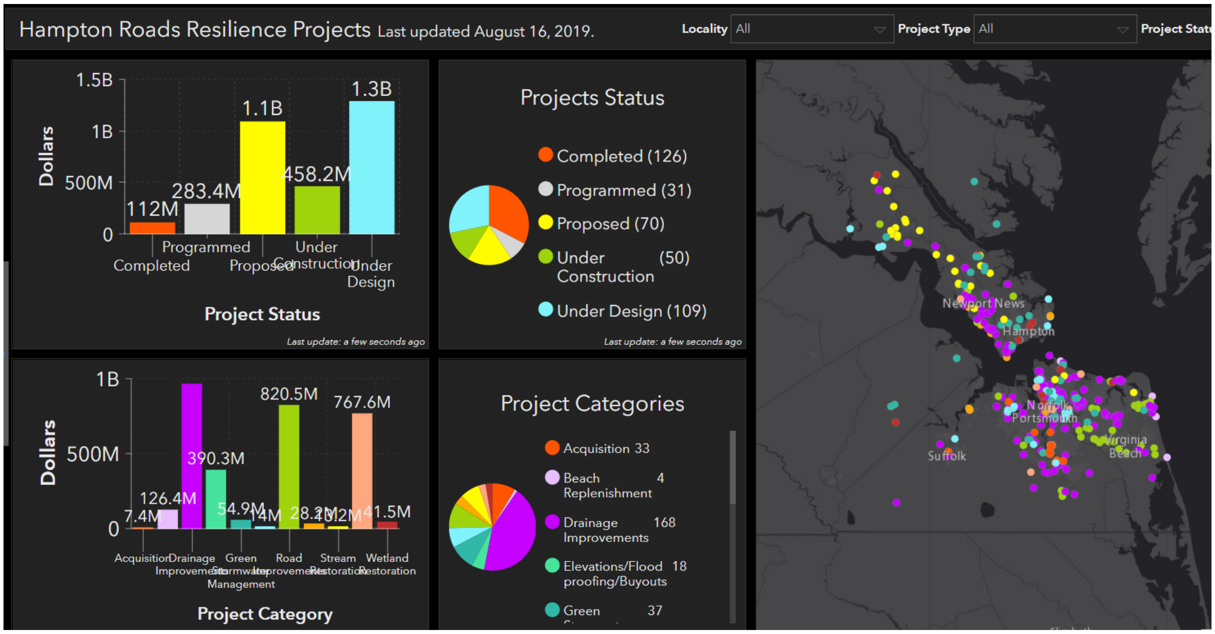

Figure 10-1. Screenshot of Hampton Roads Resilience Projects dashboard (Hampton Roads Planning District Commission)

Use the asset inventory to monitor mitigation strategies

The asset inventory can be used to collect and monitor detailed inventory data related to extreme weather events and climate change and mitigation strategies. Asset vulnerability data stored in geographic information system (GIS) or other searchable formats is useful to find assets that are not performing as desired. These assets may have more exposure to a particular hazard or be more sensitive due to condition. Inventory additions such as new asset classes, subsets of assets, or asset characteristics can aid in managing the implementation of strategies.

10.2 Track Changes in Vulnerability Indicators

The change in the value of vulnerability proxy indicators or vulnerability assessment scores over time can provide a sense of the increase or decrease in the overall risk profile. Proxy indicators can be related to hazard exposure, sensitivity, or adaptive capacity. Aspects of the risk profile may steadily decrease as certain assets are hardened or replaced with more resilient ones. Alternatively, the risk profile can increase as hazard exposure areas increase (e.g., due to sea level rise) or the rate and magnitude of change in exposure rises, such as if the fire threat increases during a particularly hot, dry season, or the frequency of storm events rises.

10.3 Monitor Cost of Extreme Weather Events

Another way to monitor the effectiveness of risk mitigation strategies is to track the damage and costs of responding to them. The tracking could be both system wide and specific to sites that have been mitigated. Tracking of the costs could include contracting costs and the cost of labor, equipment, and materials used to respond to emergency events. It is useful to track the location, time, and cost/extent of damage.

Transportation agencies can organize weather-related impact information into a master database to make collected information accessible and useful. Agencies can use databases and associated GIS maps to collect, view, and analyze impacts from extreme weather events and adjust risk mitigation plans accordingly. They can use event codes to tracks costs and impacts. For example, **Caltrans** has developed a GIS database on historical emergency maintenance events (see *Section 3.1: What are the relevant hazards?*). With this information, agencies can assess the location, frequency, and cost of responding to emergency events over time. Such information also may complement bridge and pavement management systems by providing information on the number and type of damages bridges or pavements received.

10.4 Integrate Risk Mitigation Strategy into Other Plans

The extreme weather risk mitigation strategy can easily complement many other relevant documents, plans and processes. For example, updates to extreme weather events and climate change risk mitigation strategies can assist with updates to the transportation asset management plan. The status of weather-related and changing environmental conditions and the progress made on their mitigation provide valuable information for the asset management plan risk analysis.

The STIP can also include a discussion of how the mitigation strategies are influencing the planning process which leads to a program of projects. The integration of the TAMP's risk mitigation plan into the planning process can ensure that it is integrated into decision making. The risk management plan lends itself to influencing the LRTP, the STIP, and the annual work plans for agency divisions. Risk mitigation strategies may also influence project development and scoping.

Consider including in the TAMP Monitoring Plan: Process for tracking risk mitigation strategies to extreme weather and future environmental conditions

Detail the agency's plan for monitoring the effectiveness of risk mitigation strategies as well as changing risks from extreme weather events and climate change.

10.5 Recap of Integrating Resilience into the Monitoring Plan

A monitoring plan allows an agency to track the implementation and effectiveness of mitigation strategies and monitor changes in environmental conditions to determine if it should take additional action. Table 10-1, can be used to check off actions an agency has already taken to monitor risks and resilience efforts and prioritize remaining actions.

Table 10-1. Checklist of Potential Actions for Monitoring Risk and Resilience Efforts for Transportation Asset Management

Complete?	What to analyze?	What to include?
	Monitor the implementation and effectiveness of mitigation strategies through processes such as the risk register or asset inventory.	Utilize components of the risk management process to monitor risks and mitigation efforts over time.
	Monitor changes in vulnerability over time and adjust resilience efforts as needed.	Use the risk management process to monitor changes in likelihood and consequences over time for certain risks. Update vulnerability proxy indicators as needed.
	Monitor damage from extreme weather events and climate change.	Use tools such as GIS or databases to track damage by location, time, extent of damage and asset type.
	Monitor the cost of extreme weather events over time and adjust resilience efforts as needed.	Track costs such as contracting labor, equipment, and materials that are used by in-house forces to respond to emergency events.

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APPENDIX – ASSET MANAGEMENT, EXTREME WEATHER, AND PROXY INDICATORS PILOT SUMMARY

OVERVIEW OF THE PILOT PROGRAM

The Moving Ahead for Progress in the 21st Century Act (MAP-21) (Pub. L. No. 112-141) amended 23 U.S.C. 119 to require State Departments of Transportation (DOTs) to develop risk-based Transportation Asset Management Plans (TAMPs). As State DOTs build their asset management programs and develop their TAMPs, it is important that they address risks posed by extreme weather events and future environmental conditions and consider their effects on life-cycle planning over the service life of bridges, pavements, and other assets.

From 2017 to 2019, the Federal Highway Administration (FHWA) and six State Departments of Transportation (DOTs) (see Figure 10-2) – Arizona, Kentucky, Maryland, Massachusetts, New Jersey, and Texas —piloted approaches to incorporate information on resilience into asset management programs and TAMPs, and developed additional proxy indicators to use to assess vulnerabilities. The pilot program was jointly sponsored by the FHWA Office of Environment, Planning, and Realty, and the Office of Infrastructure.

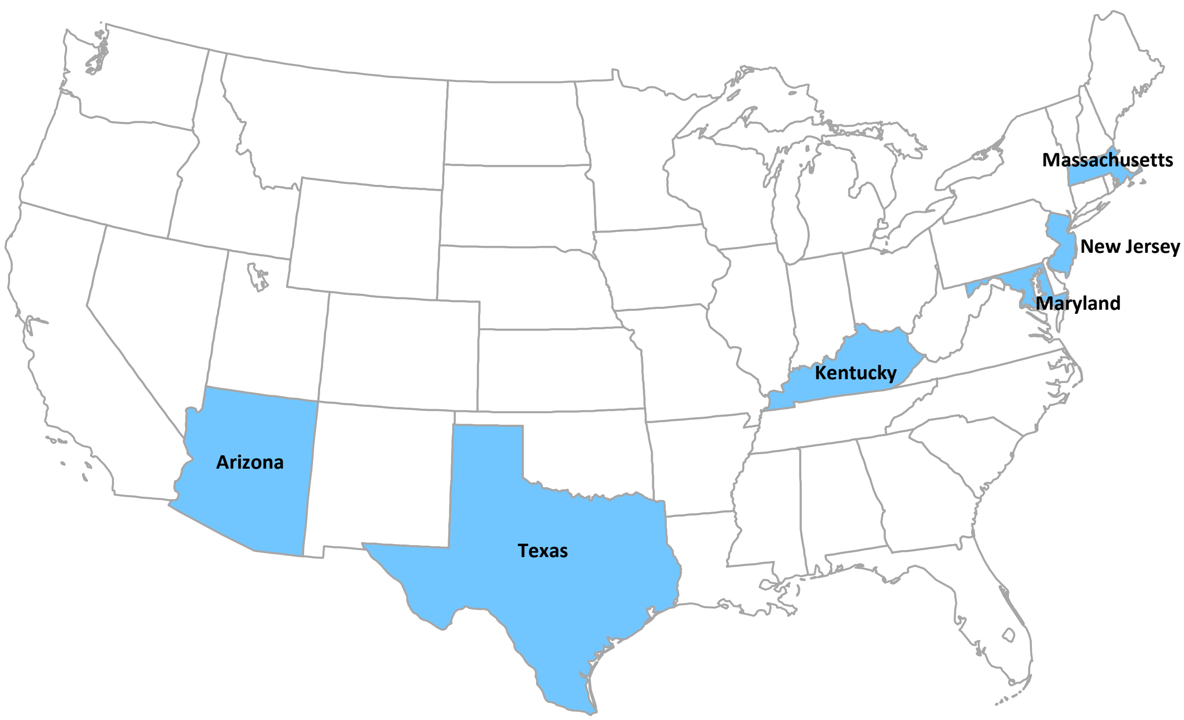

Figure 10-2. Asset management, extreme weather, and proxy indicators pilot participants.

Over the course of the pilot program, the pilot participants engaged with FHWA and each other in a series of webinars and peer exchanges. Through these events, the State DOTs shared information and lessons learned on key issues, such as assessing extreme weather and future environmental condition related risks, life-cycle planning, financial planning, and enhancing communications.

The following case studies highlight the scope, methodologies, and results for each of the pilot projects. The full final reports are available at https://www.fhwa.dot.gov/asset/pilot/.

Arizona Department of Transportation

Scope

Over the past decade, the Arizona Department of Transportation (ADOT) has undertaken a variety of projects that combine risk, science, technology, and engineering to improve the understanding of weather-related risks to its transportation system, in order to accomplish the agency's mission of "Connecting Arizona. Everyone. Every Day. Everywhere."

Building upon this work, the purpose of ADOT's pilot project was to advance a life-cycle planning approach that addresses the effects of extreme weather conditions on ADOT's transportation assets. The pilot sought to advance an approach that builds resilience and reduces risk across all elements of the asset life-cycle, from advance planning, through design and construction, and into operations and maintenance.

Approach

ADOT's pilot project involved two primary activities:

Create a Geographic Information System (GIS) Resilience Database

The team developed an integrated GIS database to enable ADOT staff to identify locations and sections that are at highest risk from the impacts of climate stressors. To create the database, the team collected georeferenced data on both stressors (flooding, wildfire, and drought) and assets (culverts, bridges, road pavement, and roadside/vegetation) from a variety of internal and external sources. Data sources included:

- United States Geological Survey (USGS) data, including stream flood gauge locations and measurements, and historical crop (vegetation) coverage.
- Live data feeds from the Federal Emergency Management Agency (FEMA), the National Weather Service (NWS), the National Oceanic and Atmospheric Administration (NOAA), the Geospatial Multi Agency Coordination site (GeoMAC), and the National Resources Conservation Service (NRCS).
- Input from ADOT district staff to identify over 500 locations currently experiencing weather-related risks.
- ADOT asset data.

The team integrated the weather-related incident data, infrastructure information, and live feeds into one geodatabase - the Resilience GIS Database. Staff can use this database to visualize and identify broad locations – i.e., corridors, sections, and structures – most at risk from climate stressors. Users can select layers, as needed, to conduct different analyses, such as synthesizing risks by stressor or by asset or asset class affected.

Develop a Life-cycle Planning Template for Assets that are Subject to Natural Hazard Impacts

The team developed a risk-based life-cycle planning template that staff can use to carry out an eight-step process to link stressors, their corresponding weather-related risks, and impacts to the infrastructure (Figure 10-2). Practitioners can use the template to prioritize risks, and to identify mitigation and adaptation options throughout the different stages of an asset life-cycle, including planning, design/engineering, maintenance, and operations.

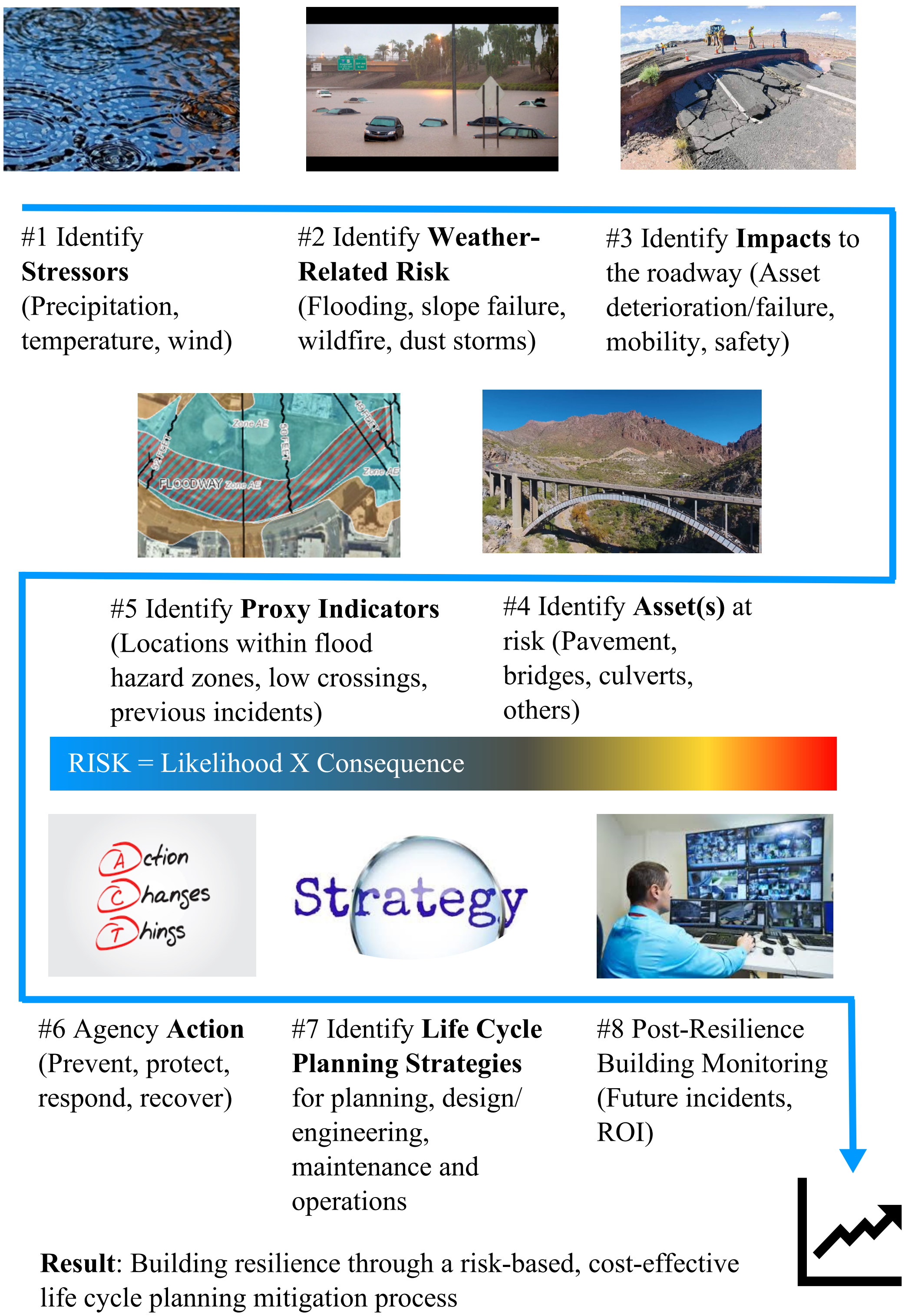

Figure 10-3. Life cycle planning template process. (AZDOT)

As part of the pilot, the team developed a template to address system flooding. Practitioners can use the template to rank risks from system flooding using indicators for asset deteriorations/failure, mobility, and driver safety/accidents. For system flooding, the impact indicators include:

- **Asset Deterioration/Failure**: pavement rutting, cracking, potholes, heaving, washouts, erosion, slope failures, and others.
- **Mobility**: closures and disruptions to the system, including temporary closures, permanent closures, detours/evacuation routes.
- **Safety**: low visibility and accidents due to weather conditions.

Practitioners can use the template to rank risks by multiplying a likelihood scale by a potential consequences scale to obtain a risk rating. The ratings of likelihood depend on past incidents or future exposure (e.g., pavement rutting, scour critical location, overtopping, etc.), while the consequence rating refers to how critical the impact has been or would be in the future.

Practitioners can then use the template to identify appropriate agency actions to address the risk. Actions may include:

- **Prevention:** Vulnerability and risk assessments; hardening of structures and materials; detection and monitoring; asset management techniques; resilience plans
- **Response**: Training; emergency response guidelines; practice drills; alternative service strategies
- **Recovery**: Alternative routing; fast contracting and project initiation; staff allocation plans
- **Investigation (root-cause):** Engineering studies; probabilistic analysis; service planning reviews
- **Learning:** After action reports; research; performance assessments

Key findings and next steps

ADOT's pilot project presents a way to integrate extreme weather and climate adaptation design into asset management by focusing on a life-cycle planning approach to identify cost-effective mitigation and adaptation strategies by asset or asset class. ADOT plans to further refine and improve the proposed risk-based approach and the GIS Resilience Database.

Phase 2 of the project will involve developing additional life-cycle planning templates that consider risks associated with drought-related dust storms, increased surface temperatures, intense precipitation, rockfall incidents, slope failures, wildfire, and wildfire-induced floods. The agency also plans to incorporate additional field-tested, emerging mitigation practices, and staff recommended practices into the templates.

Challenges and lessons learned

- Involving practitioners within ADOT, especially at the District level, was vital to developing and enhancing the templates and overall process. District staff provided information and observations about historical and current conditions that contributed greatly to the project.

- The pilot project team received a large amount of data in various formats that it needed to integrate into the GIS Resilience Database. The team was also tasked with creating maps to include in the life-cycle planning template development. Linking the GIS part of the pilot with the asset management tasks was challenging, but the team was able to overcome this through continuous communication with all stakeholders involved. The various working groups held several brainstorming sessions to develop a process that seamlessly integrated both parts of the project into a concise approach.

For more information

View the final report at https://azdot.gov/business/environmental-planning/programs/sustainable-transportation/resilience-program.

KENTUCKY TRANSPORTATION CABINET

Scope

The goal of the Kentucky Transportation Cabinet's (KYTC's) pilot project was to establish a framework for identifying asset risks associated with extreme weather and to incorporate risk-based information into the management of the transportation system. The pilot considered the potential impacts of two primary climate threats – extreme heat and extreme precipitation – on two major asset classes – pavements and bridges.

Approach and key findings

The project involved two major initiatives designed to enhance KYTC's ability to effectively perform asset management planning within the context of extreme weather. The first was a technical analysis to develop a screening tool to identify bridge sensitivity to flooding. The second was a technical analysis to develop a methodology for incorporating climate projection data into pavement design and performance monitoring. Following the analysis, KYTC identified a number of process improvement opportunities to promote better asset management practices.

Develop and refine flood sensitivity indicators for bridges and culverts

As part of the pilot project, KYTC developed a high-level, asset screening methodology to hierarchically analyze bridges and culverts to determine their sensitivity to flooding, scour, and other geomorphic instabilities. The methodology is designed to enable engineers, maintenance workers, and other stakeholders to quickly and cost-effectively discern risk to structures at the inventory level. KYTC's methodology does not require the collection of additional field data; rather, it primarily leverages National Bridge Inventory (NBI) data.

The flood sensitivity screening methodology calculates a Bridge and Culvert Sensitivity Index (BCSI) score for each bridge and culvert asset. The BCSI is a holistic representation of how sensitive a structure is to hydraulic forcings based on three components: an asset's structural condition, geomorphic sensitivity, and criticality.

- **The Structural Condition score** offers insights into bridges and culverts that are susceptible to high-magnitude flooding and geomorphic instabilities. It can be used to quickly discern the overall structural integrity of a bridge based on NBI data. For bridges, the methodology uses three indicators to calculate the structural condition score: the condition of a structure's deck, superstructure, and substructure (NBI Items 58-60). For culverts, NBI Item 62 (culverts) alone is used to calculate the structural conditional score.
- **The Geomorphic Sensitivity score** indicates the sensitivity of a bridge based on its environment, such as bank composition, vegetation cover, erosion control features, and channel sinuosity. It leverages data on channel condition, scour potential, and observed scour. The Geomorphic Sensitivity score is calculated using fix indicators, three items from the NBI and two KYTC-specific factors: 1) NBI Item 61: Channel and Channel Protection; 2) NBI Item 71: Waterway Adequacy, 3) NBI Item 113: Scour Critical

Bridges, 4) KYTC Factor 1: Scour Observed, and 5) KYTC Factor 2: Scour Risk Calculation.

- **The Criticality score** measures how integral an asset is to the transportation network. The criticality score is calculated using five NBI elements: 1) NBI Item 19: Bypass Detour Length, 2) NBI Item 29: Average Daily Traffic (ADT), 3) NBI Item 49: Structure Length, 4) NBI Item 104: Highway System of the Inventory Route, and 5) NBI Item 109: Average Daily Truck Traffic.

Key findings from flood sensitivity screen

The KYTC project team used the methodology it developed to conduct a hierarchical screening (see Figure 10-4) of the over 7,300 bridges and culverts that the agency owns and maintains.

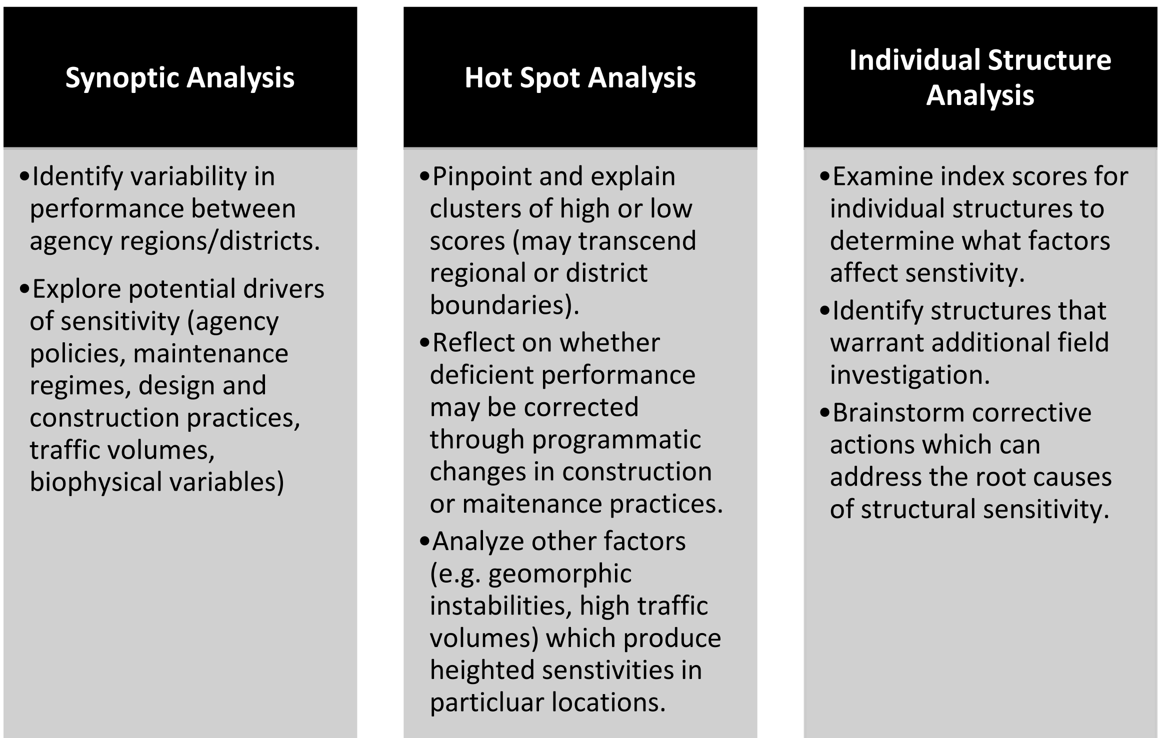

Figure 10-4. Hierarchical framework for analyzing bridge and culvert inventories. (KYTC)

The team first conducted a synoptic analysis, which focused on the condition and performance of structures at the statewide level, to determine where variability exists between regions or districts and identify potential explanations for those differences. Next, the team conducted a more focused "hot spot" analysis that focused on particular areas in which there are clusters of sensitive bridges and culverts. KYTC's hotspot analysis found several areas of high BCSI scores, including in the north-central portion of Kentucky (District 5), primarily around the city of Louisville and extending northeastward, and in the southeastern part of the state (District 11). The most intense clustering in District 5 is found located along a band that parallels the Kentucky River from the northern portion of Franklin County downstream toward its junction with the Ohio River. Some of this clustering may be due to the highly erodible shale in the region. High Geomorphic Sensitivity Index scores in Districts 9 and 11 are likely due to the considerable topographic relief (i.e., the amount of topographic change) present in these areas. The terrain is more mountainous, with the headwaters of the Middle Fork Kentucky River and South Fork Kentucky River both located in the area. Streams located in the upper and upper-middle portions of watersheds generally have higher potential stream power because of steeper gradients, which increases their capacity to move sediment (e.g., instigate bridge scour).

Lessons learned and next steps

KYTC views the methodology it developed to evaluate the sensitivity of its bridges and culverts to flooding as a springboard to inform its structure management program. While the methodology accurately represents the performance and sensitivity of an entire inventory, decisions about where to direct future investments should not be made based on these results alone. KYTC suggests that after locating clusters of structures or the regions in which structural sensitivity is high, ideally agencies will look more closely at individual structures to better understand why they are sensitive and how that sensitivity can be mitigated. Only with this knowledge can agencies make informed decisions about not just countermeasures but also project prioritization.

Modeling pavement performance to extreme heat in future climate scenarios

The second aspect of KYTC's pilot projects was to investigate the viability of using climate projection data to model pavement performance. KYTC used Pavement ME, a performance prediction tool that predicts the performance of a pavement structure over time, given specific design characteristics, traffic loadings, and climate conditions.

The KYTC project team used the USDOT's *Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool* to identify and obtain statistically downscaled climate projection data for Kentucky for two future 20-year time periods (2020-2039 and 2040-2059). Because the effort was designed to be a proof of concept to analyze the impacts of extreme weather, KYTC used the Representative Concentration Pathway (RCP) scenario, which represents the highest emissions scenario.

The project team had to further process the climate projection data so that it was in the proper format to be used as climate input files for the Pavement ME software. This involved processing the data to produce average daily temperature and precipitation readings, adjusted for projected extreme weather occurrences, and then interpolating the climate projection data to the hourly level and matching it with historical data from the Pavement ME software climate file.

Key findings from pavement performance modeling

The project team used the Pavement ME software to predict pavement performance for both a 20-year and 40-year anticipated pavement life for a standard current pavement design in the Bowling Green area, one of the warmer regions of the state. Data inputs such as traffic and pavement design were held to current data so that the only variation in running the pavement model was the climate conditions.

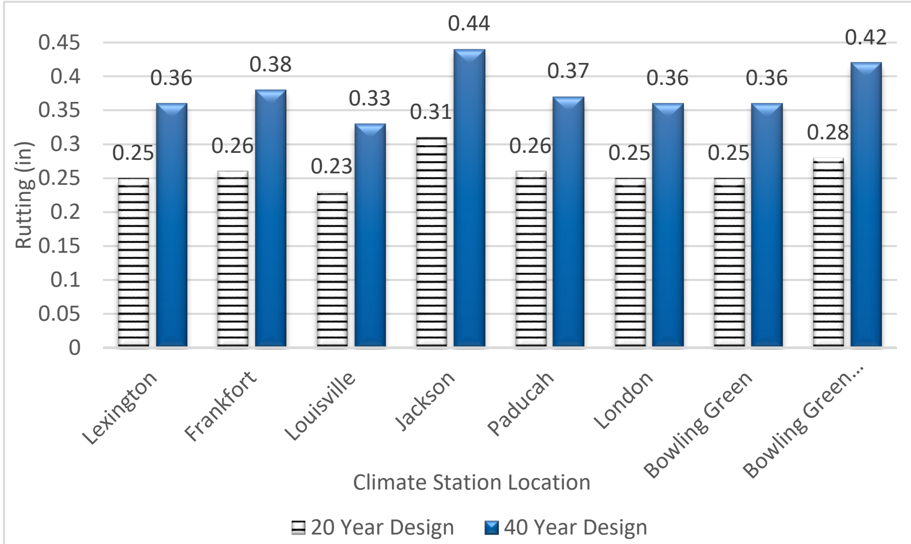

Figure 10-5. Predicted asphalt rutting. (KYTC)

The Pavement ME model predicts an increase in pavement rutting and fatigue cracking as a result of the warmer climate scenario (see Figure 10-5). However, these increases are within an acceptable range in terms of pavement performance and are not high enough to warrant altering the pavement design to withstand such hotter conditions.

Lessons learned and next steps

KYTC's proof of concept demonstrated the viability of using climate projection data as an input for pavement design and performance monitoring software. However, further research is needed to better understand the viability of using data from climate models as an input to pavement design software. For example, a thorough sensitivity analysis may be helpful to investigate at what levels temperature increases begin to result in more pavement damage.

KYTC process improvements

Over the course of its pilot project, KYTC identified opportunities to improve existing processes to better account for extreme weather and promote system resilience. When the team recognized that the agency lacked a system to track and locate areas that have had Emergency Relief (ER) repairs, they sought to develop a centralized Geographic Information System (GIS) database to track the locations and details for ER projects going back to 2009. This database will assist KYTC in fulfilling its 23 CFR Part 667 requirements. KYTC also updated the internal processes used to assign activities to ER projects to better account for activities outside the immediate scope of ER activities, such as National Environmental Policy Act (NEPA) analyses triggered by an ER event. As a result, the agency has completed and processed environmental documents for ER projects in a more expedited manner, and as a result, has expedited the process by which KYTC is reimbursed.

The KYTC project team identified additional process improvements that it will continue to pursue following its pilot effort. These include:

1. Continue to integrate KYTC systems that track and monitor all costs associated with ER events.
2. Develop KYTC maintenance activities that can proactively prepare for extreme precipitation in advance of the event.
3. Establishment of a Resilience Working Group to foster communication, collaboration, and promote best practices to improve resilience throughout the agency.
4. Continue to incorporate of extreme weather risk into asset management and KYTC's Transportation Asset Management Plan (TAMP).

For more information

View the final report at https://www.fhwa.dot.gov/asset/pilot/ky.pdf

Maryland Department of Transportation State Highway Administration

Scope

As of 2019, the Maryland Department of Transportation State Highway Administration (MDOT SHA) manages over 73,000 lane miles of road and over 5,300 bridges. Several of these assets experience flooding, whether from extreme rain events (such as the devastating floods in Ellicott City in 2016 and 2018) or from extreme high tides or storm surge in Maryland's low-lying coastal areas. As these events persist and potentially worsen into the future, MDOT SHA is seeking to ensure the resilience of the state's transportation system through, among other means, an asset management program that minimizes risk and optimizes state resources.

In 2014, MDOT SHA completed a pilot climate change vulnerability assessment to identify specific roads and bridges most vulnerable to flooding in Anne Arundel and Somerset counties. In 2018, MDOT SHA's asset management, extreme weather, and proxy indicators pilot project built upon this work to:

- Refine the vulnerability assessment approach and expand the assessment to cover bridge structures statewide, and
- Identify and implement specific opportunities to integrate the vulnerability assessment results—and other information about climate risks—into existing MDOT SHA asset management, planning, and other processes.

Approach

The MDOT SHA conducted an indicator-based vulnerability assessment using the FHWA Vulnerability Assessment Scoring Tool (VAST) to identify bridge assets vulnerable to three climate hazards: sea level change, storm surge, and precipitation change. The agency used data on asset location and other key attributes to serve as indicators of each of the components of vulnerability: exposure, sensitivity, and adaptive capacity. The agency used different indicators for each of the three climate hazards (see Table 12-1).

The team assigned scores to each indicator to develop a vulnerability score for each asset across the three climate hazards. Each indicator received a different weight toward the overall vulnerability score.

Table 10-2. Vulnerability Indicators for Sea Level Change, Storm Surge, and Precipitation Change Hazards

Component	Sea Level Change (SLC)	Storm Surge	Precipitation Change
Exposure	Modeled SLC Inundation Depth (2050 Mean Higher High Water)	Modeled Surge Inundation Depth (0.2% annual chance storm in 2050)	Location relative to Federal Emergency Management Agency (FEMA) Flood Zones
	Proximity to Coastline	Proximity to Coastline	Percent change in 24-hour, 50-year precipitation

Component	Sea Level Change (SLC)	Storm Surge	Precipitation Change
Sensitivity	Past Experience with Tides/SLC	Past Experience with Storm Surge	Past Experience with Precipitation
	Underclearance	Underclearance	Underclearance
	Scour Rating	Scour Rating	Scour Rating
	Bridge Age as of 2018 (from most recent reconstruction)	Bridge Age as of 2018 (from most recent reconstruction)	Bridge Age as of 2018 (from most recent reconstruction)
	Condition of Bridge Substructure	Condition of Bridge Substructure	
	Condition of Bridge Superstructure	Condition of Bridge Superstructure	
	Condition of Bridge Deck	Condition of Bridge Deck	
Adaptive Capacity	Functional Classification	Functional Classification	Functional Classification
	Evacuation Route	Evacuation Route	Evacuation Route
	Detour Length (overall increase in path length due to a detour around a flooded structure)	Detour Length (overall increase in path length due to a detour around a flooded structure)	Detour Length (overall increase in path length due to a detour around a flooded structure)
	Average Daily Traffic (ADT)	Average Daily Traffic (ADT)	Average Daily Traffic (ADT)

Key findings

The assessment identified that, of the 8,588 structures evaluated, 33 are highly vulnerable to sea level change, 172 are highly vulnerable to storm surge, and 102 are highly vulnerable to precipitation change.

Assets with high vulnerability to sea level change are concentrated in MDOT SHA Districts 1, 2, and 5. Those same districts share vulnerability to storm surge, with the addition of District 4. Assets with high vulnerability to precipitation change are spread across all Districts, with the highest concentration in MDOT SHA Districts 4 and 7.

Integrating results into MDOT SHA practice

The project team conducted a series of working sessions with MDOT SHA staff to discuss opportunities and strategies for integrating the results of the vulnerability assessment into existing asset management systems and processes, including pavement asset management, bridge asset management, planning, and operations. The sessions involved staff from the following departments:

- Office of Materials Technology
- Office of Structures
- Office of Planning and Preliminary Engineering
- The Coordinated Highways Action Response Team

During each working session, the project team facilitated a review of the available vulnerability assessment results, discussion of the climate risks in the Transportation Asset Management Plan (TAMP) risk register, and discussion of ways to apply the climate risk information.

Through the working sessions, the team identified several opportunities to use the climate risk information in asset management and other processes. The actions included specific strategies for using the risk information in decision-making, as well as smaller, incremental steps necessary to enable those processes. Highlights of the strategies MDOT SHA is taking as the result of this pilot project include:

- **Update pavement performance models to reflect current and expected inundation frequency.** This will ensure inundation is captured in expected deterioration rates and automatically factored into existing processes for prioritizing and financing maintenance and other investment priorities.
- **Create and implement a process to screen projects involving any new structures for climate risk.** This will help the agency take advantage of existing repairs or replacement projects to address climate risks as appropriate.
- **Incorporate climate risk into the project Purpose and Need.**
- **Create a climate risk vulnerability viewer and disseminate climate risk data throughout the agency and its partners** to ensure all are aware of the information and its applications to decision making. Where possible, the agency will seek to create formal processes to ensure staff consult the climate risk data view at relevant junctures.

All of these strategies—and the supporting actions necessary to achieve them—will help MDOT SHA reduce life-cycle costs of their infrastructure.

Next steps

MDOT SHA has taken and will continue to take steps to integrate findings from this pilot project. Crosscutting next steps include:

- Improve and finalize the online interactive Climate Change Vulnerability Viewer App, which includes road and bridge vulnerability data, and related future flooding information.
- Implement a process for tracking flood-related road closures.
- Continue to disseminate climate risk information through coordination meetings, lunch and learn meetings, and other venues.
- Complete implementation of all short-term action items and begin longer-term integration strategies.

Lessons learned

Overall, MDOT SHA's pilot project demonstrated several practical actions that the agency can take to incorporate climate risk into their asset management and other systems. Furthermore, through this pilot project MDOT SHA identified several key lessons about the process of integrating climate risk into asset management. These include:

- Working sessions are effective in focusing attention and generating ideas for climate risk integration into planning, asset management, and other decision-making processes.
- It is important to tailor communication with staff to account for their existing concerns, understanding of climate risk, time available to devote to the topic, and data used for decision making.
- Different offices and individuals will have different data needs. It is therefore important to be flexible and able to develop customized datasets for different users.
- It is not always possible to know what the most useful data will be at the beginning of the vulnerability assessment.
- It is important for potential users of the climate vulnerability results to understand and accept the assessment methodology.
- In an indicator-based vulnerability assessment, users need to be able to understand not just the final vulnerability ratings but also their constituent parts.
- Capturing data on past experiences with flooding is critical to contextualizing and understanding future potential vulnerability. Capturing data is more effective using a simple spatial (map-based) format.
- Historical flooding events have typically not been comprehensively documented in a format that is accessible, leaving a data gap.
- Climate change prompts difficult decisions, some of which may require high-level guidance or other adaptation actions that go beyond individual asset management decisions.

For more information

View the final report at https://www.fhwa.dot.gov/asset/pilot/md.pdf

MASSACHUSETTS DEPARTMENT OF TRANSPORTATION

Scope

The purpose of the Massachusetts Department of Transportation's (MassDOT's) pilot project was to perform an initial statewide flood resilience screen of culverts and bridges. The pilot project examined over 1,100 culverts owned by MassDOT and over 2,700 bridges owned by MassDOT or a municipality. The project builds upon the Deerfield River Watershed Pilot Study[5], which screened culverts for flood resilience in the Massachusetts portion of the watershed. The Deerfield River Watershed study identified percent bankfull width and specific stream power as strong indicators of past culvert failure.

Approach

Estimate structure vulnerability

The MassDOT pilot project team assessed a structure's vulnerability based on its geomorphic compatibility (i.e., how well a structure matches the channel in which it is located in) and its potential channel erosion vulnerability. The team used the following proxy indicators to estimate each element:

- **Geomorphic compatibility**: Percent bankfull channel width (i.e., structure width divided by bankfull channel width) was used to initially assess each structure's geomorphic compatibility (i.e., how well a structure matches the channel in which it is located in). The team estimated bankfull channel width for all stream segments using the current US Geological Survey (USGS) regional hydraulic geometry regression equation for Massachusetts:

$$W_{bankfull} = 15.0418 \text{ x Drainage area}^{0.4038}$$

- **Channel bed erosion**: The methodology used specific stream power (SSP) and predicted riverbed resistance as proxy indicators to estimate channel bed erosion**.** Stream power works in balance with the resistance of the channel bed and banks and influences channel pattern, channel profile, sediment transport, channel stability, and response to floods. SSP, which defines the rate that potential energy is supplied to a unit area of the channel bed, is calculated using the weight of the water, flow, channel slope, and the bankfull channel width. The project team calculated the bankfull discharge for each stream segment in the NHDPlus HR dataset by estimating the 2-year flood using the current USGS Massachusetts regression equations[6]. The team obtained channel slope and drainage area for each stream segment directly from the NHDPlus HR dataset. The team

[5] MMI, 2017. Stream Power Assessment Report Including Culvert and Bridge Vulnerability Analysis, Deerfield River Basin, Massachusetts and Vermont, Huc 01080203. Prepared by Milone & MacBroom for, and in collaboration with, the University of Massachusetts and Massachusetts Department of Transportation, Cheshire, CT.
[6] Zarriello, P. J., 2017. Magnitude of Flood Flows at Selected Annual Exceedance Probabilities for Streams in Massachusetts (Https://Doi.Org/10.3133/Sir20165156). U.S. Geological Survey Scientific Investigations Report 2016–5156.

predicted riverbed resistance for each NHDPlus HR stream segment using Massachusetts surficial geology geographic information system (GIS) data. The predicted bed resistance was combined with the estimated specific stream power to estimate the potential channel erosion vulnerability for all of the NHDPlus HR stream segments in Massachusetts.

The project team combined the scores for estimated structure geomorphic compatibility and potential channel erosion vulnerability to develop an estimated structure vulnerability score (Figure 10-6) for each for each of the MassDOT bridges and culverts included in the study.

		Estimated Structure Geomorphic Compatibility		
		Low	Moderate	High
		($\%_{Wbankfull} < 50$)		($\%_{Wbankfull} \geq 100$)
Potential Channel Erosion Vulnerability (SSP and Bed Resistance)	High	H	H	M
	Moderate	H	M	L
	Low	M	L	L

Figure 10-6. Estimated structure vulnerability scoring. (MassDOT)

Considering climate change

As part of the pilot project, the team analyzed how the impacts of climate change may affect flood resilience in the future. Mean annual precipitation in Massachusetts is expected to increase 5-10% in the next 50 years[7]. In order to develop an initial prediction of increased flows due to climate change, the project team applied the projected increase in mean annual precipitation to estimates of bankfull discharge for each stream segment. The team then calculated changes in potential channel erosion vulnerability and estimated structure vulnerability due to increases in bankfull flow to identify segments potentially more vulnerable due to climate change.

Key findings

The analysis found that most of the MassDOT culverts examined in the study have moderate to high estimated vulnerability (Figure 10-8), while most bridges have low to moderate estimated vulnerability (Figure 10-7). Culverts in particular pose a difficult management challenge because many are undersized and do not fit the channels in which they are located. The widespread undersized nature of culverts is a function of traditional design approaches that sized structures with a focus on clear-flow hydraulics (i.e., without consideration of sediment, large wood, and ice).

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[7] Northeast Climate Adaptation Science Center, 2018. http://resilientma.org.

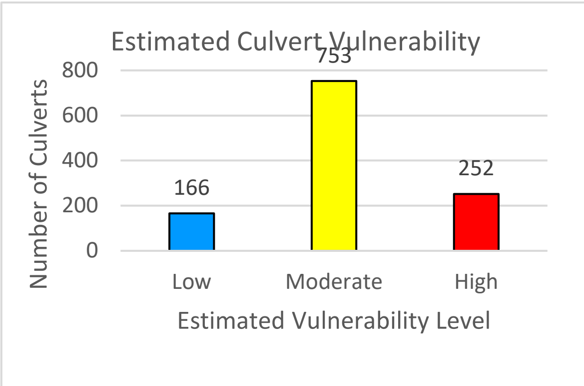

Figure 10-8. Summary of estimated culvert vulnerability. (MassDOT)

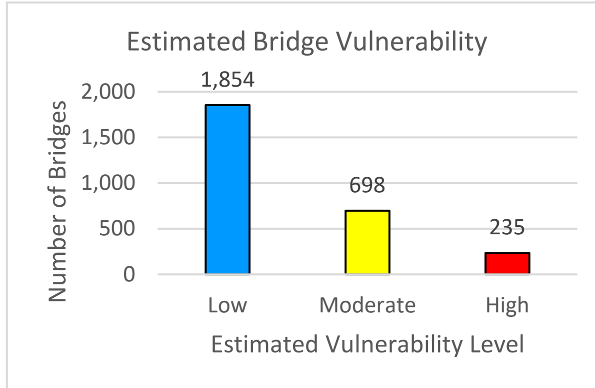

Figure 10-7. Summary of estimated bridge vulnerability. (MassDOT)

The increased size and frequency of future floods predicted to take place with a changing climate will increase potential channel erosion and structure vulnerability. Larger floods and increased stream power translate to more channel erosion, and crossing structures needing to pass more water, sediment, and large wood. The analysis found that by the 2070s, estimated vulnerability may increase at 108 culverts and 53 bridges due to climate change.

Next steps

This study, combined with the ongoing construction of the MassDOT Culvert Database, constitutes part of the first step of the life-cycle planning process. The wide distribution of culverts predicted to have high vulnerability across the Massachusetts transportation system, and the potential for widespread increases in vulnerability due to increased flows with changing climate, illustrate the importance of performing life-cycle planning for culverts. This work begins the process of bringing culverts into the MassDOT Transportation Asset Management Plan (TAMP).

The data from this and other MassDOT resilience studies will inform the development of a culvert life-cycle planning process. Based upon the results of this study, MassDOT will identify and address next steps for the integration of culverts into its asset management efforts, including:

- Further validation of screening results against past damages;
- Conduct field inspections at the high-vulnerability culverts and bridges;
- Begin a culvert inspection program;
- Import the results into Massachusetts GeoDOT - the MassDOT Geographical Information System (GIS) portal for viewing, creating, and sharing GIS data - to create online GIS maps to view the screen results and update the screens as additional culvert information is obtained;
- Add the results to the Massachusetts Project Intake Tool (MaPIT) to accompany other resilience information and improve project development and design.
- Complete the development of the MassDOT Culvert Database;
- Advance the life-cycle planning process for culverts;

- Coordinate with FHWA on the potential for a culvert replacement and improvement program;
- Add culverts to the TAMP; and
- Refine the analysis used in this study at culverts added to the MassDOT Culvert Database in the future.

Lessons learned

The primary use of the screening methodology used in the pilot project was to initially screen river and stream crossing structures for red flags where vulnerability could be high to moderate and data are limited. This work is more relevant to culverts because bridge data are readily available through periodic inspections. While the resilience screen results are useful for observing possible vulnerabilities, they are not yet suitable for alternatives analysis or design. The resilience screen is intended to guide planners and designers to vulnerable structures around Massachusetts to confirm results and initiate projects to ultimately improve the resilience of the transportation network. This work does not replace structure condition assessments or hydraulic evaluations that are essential for understanding the remaining life of a bridge or culvert. Furthermore, onsite stream geomorphic assessment is needed to verify bankfull width and potential erosion estimates.

New Jersey Department of Transportation

Scope

More frequent extreme weather events and notably flooding from more intense rains are presenting a growing challenge to New Jersey's economy, environment, and everyday way of life. This flooding not only disrupts mobility, but it also has the potential to damage roadway assets such as drainage structures including culverts, inlets, pavement, and others.

The purpose of the New Jersey Department of Transportation's (NJDOT's) pilot project was to develop a method (risk-based analytical procedure) that provides the capacity to link asset management, extreme weather, and climate resilience to reduce risks to New Jersey's highway system. The study team selected two case study areas in Passaic County (Figure 10-9) where the roadways are experiencing frequent flooding:

- Interstate 80 (I80) between milepost 56.43 and 58.22
- Route 23 between milepost 4.00 and 7.00

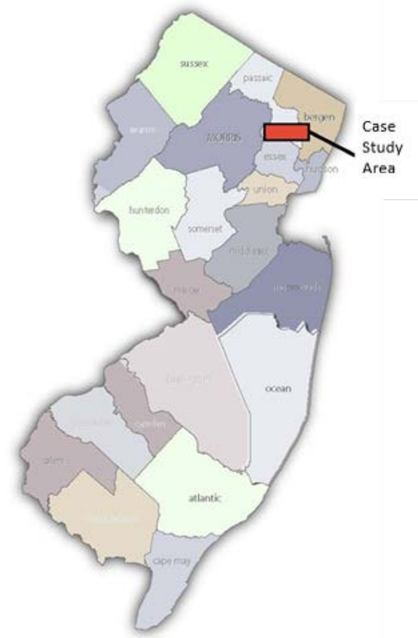

Figure 10-9. NJDOT case study area.

Between 2012 and 2017, the two sites experienced 67-recorded flooding incidents. The project team evaluated these flooding incidents to identify the vulnerable assets within these locations. The team then conducted a root cause analysis to determine the factors contributing to flooding at these locations and proposed appropriate life-cycle planning mitigation solutions.

Approach

The work effort for this study included intensive data collection, analysis of data, and geographic information system (GIS) intersection analysis to fully assess the impacts to the roadway at the selected case study areas. Data was gathered for the various stages of the vulnerable assets' life-cycle (initial construction – existing design/engineering, to maintenance and operations) to determine contributing factors to poor drainage and flooding at each of the life-cycle stages, from initial design/engineering through maintenance and operation. Based on the root cause analysis, the team developed short-and long-term adaptation/mitigation solutions to address flooding at each location.

Key findings

The study team identified the following as contributing factors to the poor drainage and flooding at the two study sites:

Initial Construction (Original Design/Engineering – Current Condition)

- Pavement in poor condition (current condition)

- Flat cross slopes – water does not quickly and easily leave the roadway causing safety impacts
- Inadequate inlet spacing resulting in flooding that results in lane closures
- Insufficient superelevation on all curves
- Insufficient widths of right and left shoulders
- Culverts are not contributors to flooding at this location
- Others not applicable to this study

Maintenance/Operations

- Limited resources for the increased sweeping of the roadway needed to maintain segments free of debris that contribute to the clogging of inlets and drainage structures.
- Need for higher quality control during pavement resurfacing projects to avoid ponding of water by creating local low points.
- Limited funding to address drainage issues as part of pavement resurfacing projects.
- Limited resources to carry out cleaning activities of drainage assets to avoid drainage structures clogging prior to storm events, and as a reactive activity after heavy precipitation events.

Figure 10-10: Accumulated debris on culvert rack (I-80 Milepost 57.3 Structure #1610177). (NJDOT)

The team obtained downscaled climate and hydrology projections as part of the data analysis to identify future climate and precipitation changes that may further affect the case study areas. The climate projections indicate that extremely heavy 24-hour precipitation amounts are expected to increase by 9%. This projected increase will continue to affect the case study areas and other at risk-locations.

Recommended mitigation strategies

The team identified the following cost-effective mitigation strategies to build resilience against increased precipitation events for the individual transportation facilities studied. Some of the recommendations could be applicable to other locations where similar conditions exist.

Planning

- Strengthen data collection methods to record lane closures and monitor other extreme weather impacts.
- Increase communication within NJDOT units regarding known vulnerabilities and ways to address these by different organizational units and functions.
- Add planned projects in GIS tool to identify projects in vulnerable areas and integrate resilience and vulnerability information into NJDOT's project delivery process.

- Document and communicate the root-cause method piloted in this study as a general approach to increase resilience by identifying the most cost-effective actions to mitigate and reduce climate change risks.
- Establish a Resilience Work Group to track resilience progress
- Strengthen partnerships with other agencies (U.S. Geological Survey (USGS), the New Jersey Department of Environmental Protection, Federal Emergency Management Agency and other state and local agencies) to improve interagency coordination.

Design/Engineering (Case Study Areas - Site Specific Recommendations)

- Address substandard superelevation (cross-slopes).
- Upgrade horizontal and vertical design of roadway.
- Enhance drainage to minimize disruptions and asset deterioration; consider placing additional inlets as needed in areas identified as frequently flooded locations.

Maintenance/Operations

- Increase sweeping of roads at frequently flooded locations *(Identified as top mitigation measure).*
- Increase inspection/cleaning of culverts and drainage structures as routine maintenance and prior to rain events *(Identified as top mitigation measure).*
- Continue to monitor pavement condition for milling and crack sealing.
- Track/record weather-related closures as needed with specific fields, including road(s) closed, length of closure, duration of closure, specific lanes closed, and reason for closure.
- Monitor USGS real-time stream gages for potential temporary closures of vulnerable routes or other measures and consider use of enhanced technology (web cameras) to better monitor storm impacts and flood stages.
- Increase availability of roadway assistance vehicles and deploy emergency maintenance patrols after storm events.
- Lower speed limits during rain events (if necessary).
- Establish, revisit, and update as necessary emergency detours/evacuation routes.
- Enhance communication channels to inform travelers (enhanced Intelligent Transportation System infrastructure) about road/lane closures, detours, accidents, and road condition.
- Expand and improve methods and procedures for pre- and post-flood inspections of roadways, bridges and streams.

Lessons learned

Through the pilot project, NJDOT learned the following:

- **Understanding the root cause is key to developing cost-effective life-cycle management mitigation strategies.** In the selected case study areas, increased preventive and reactive maintenance activities would help to decrease flooding incidents.

- **Current locations at risk may not correlate to locations at risk in future inundation projections**. The study team found that current locations experiencing flooding are not included in inundation projections based on future climate change data due to different causes of flooding. It is important to plan for the future while also addressing current problems that help build resilience for future events
- **Isolating asset classes may not provide an accurate representation of problems.** The study team evaluated impacts to the road and saw the need to study drainage systems as a whole and not isolate culverts, since the evaluation of these and their respective inspection reports did not indicate them to be direct contributors to flooding at the case study areas.
- Incorporating the experience of day-to-day asset managers (Operations and Maintenance) in assessing the impacts of extreme weather is important. The study team overcame challenges in data collection efforts and integration of extreme weather into asset management by involving internal and external stakeholders to be part of the conversation, sharing of ideas, and project development

TEXAS DEPARTMENT OF TRANSPORTATION

Scope

The purpose of the Texas Department of Transportation's (TXDOT's) pilot project was to characterize the risk of extreme weather events to road infrastructure in Houston, Texas in order to provide better inputs for pavement engineers to estimate the damage caused by these events.

At the start of the pilot project, the study team hosted a one-day workshop with stakeholders in Houston to share the goals of the pilot project; discuss extreme weather resilience in the context of transportation infrastructure; and obtain early input and commitment from stakeholders on the study approach and potential data sources. Workshop participants also provided input on the critical elements of the TxDOT Houston District transportation network (i.e., essential corridors). During the workshop, participants agreed that the main extreme weather events in Houston are associated with water/flooding, whether from tropical storms, and hurricanes or a high rainfall event. As a result, the pilot effort focused on developing a methodology to determine the vulnerability or risk of Houston's road infrastructure to inland flooding, to determine the incidence of flooded areas with road infrastructure, and the potential infrastructure impacts attributable to flooding.

Approach

In the pilot project, the study team defined and assessed risk based on the likelihood of a flood event occurring and an estimate of the damage if a flood event occurs. In order to calculate the probability of an adverse event occurring the study team mapped the spatial and temporal pattern of floods and the height of local floodwater using two sources of spatial data: Federal Emergency Management Agency (FEMA) flood risk maps and digital elevation models (DEM) of Harris County. In addition, the team also used data on the location of rivers and water bodies, United States Geological Survey (USGS) watershed maps, and stream gage measurements. The team then used aerial Light Detection and Ranging (LiDAR) data to estimate the elevation of road surfaces and surrounding infrastructure within Harris County.

To determine the impacts of a flooding event, researchers overlaid the flood depth and road elevation data of the state-maintained network to obtain the depth of road inundation. Overlaying these two layers also allowed the study team to estimate: a) the likelihood of roads becoming impassable during floods; and b) sections most at risk to flooding because of pavement structure and the depth of floodwater (where floodwater depth is assumed to be a proxy measurement for duration and frequency of inundation).

Researchers simulated the impact of flooding on the structural capacity of selected pavement structures (i.e., rutting) using the TxME pavement design software. The team simulated different scenarios of traffic levels, pavement structures, and flooding events (regular flood events that occur within delineated floodways, as well as the 100-year and 500-year flood events) to assess the effects of flooding on the service life of flexible pavements.

The analysis looked at three pavement structures: Pavement Type 5, 6, and 10 (see Figure 10-12).

Pavement Type 5 | Pavement Type 10 | Pavement Type 6

Notes:
AC = asphalt concrete, CTB = cement treated base, LTSG = lime treated subgrade, FB = flexible base, SG = subgrade.
In the case of Structure II (Pavement Type 10), the surface layer is a surface layer that has been treated.

Figure 10-11. Pavement structures. (TXDOT)

Key findings

The pavement analysis found that thinner pavement structures, particularly those without treated subgrades and less than two inches of asphalt are particularly vulnerable to flooding. If thinner pavement sections are heavily trafficked during flood response, immediate pavement damage can be expected that will likely involve immediate reconstruction (see Figure 10-13).

The simulation results showed:

- Pavement Type 5: The typical service life of Pavement type 5 is 24 years under heavy traffic loading when there is no flood event. The simulation of a flood event immediately after pavement construction showed no impact on the service life of the pavement. However, as the pavement remains in service for 10 or more years and is flooded, the service life begins to shorten. The service life is essentially shortened by one year per event for pavements older than 10 years. The simulation also showed that when floods occur in three consecutive years, the service life of Pavement type 5 is reduced from 24 years to 21 years.
- Pavement Type 10: The typical service life of Pavement type 10 is 24 years under low traffic volume, however, the simulation results showed that when the roadway is flooded and traffic increases significantly in the year immediately after flooding, failure occurs almost immediately. Therefore, if there is a large recovery effort on roadways with a similar structure to Pavement Type 10, the managing agency should plan for immediate rehabilitation projects.
- Pavement Type 6: The simulation of flooding events on roadways with Pavement Type 6 show that under consistent low traffic volume (i.e., a recovery effort that does not include a major increase in traffic), the service life of the pavement remains unchanged regardless of the flood events. This type of structure can be a resilient structure for roadways that are trafficked predominantly by vehicular traffic (e.g., a neighborhood street). However,

similar to Pavement Type 10, Pavement Type 6 will fail quickly under heavy traffic loading.

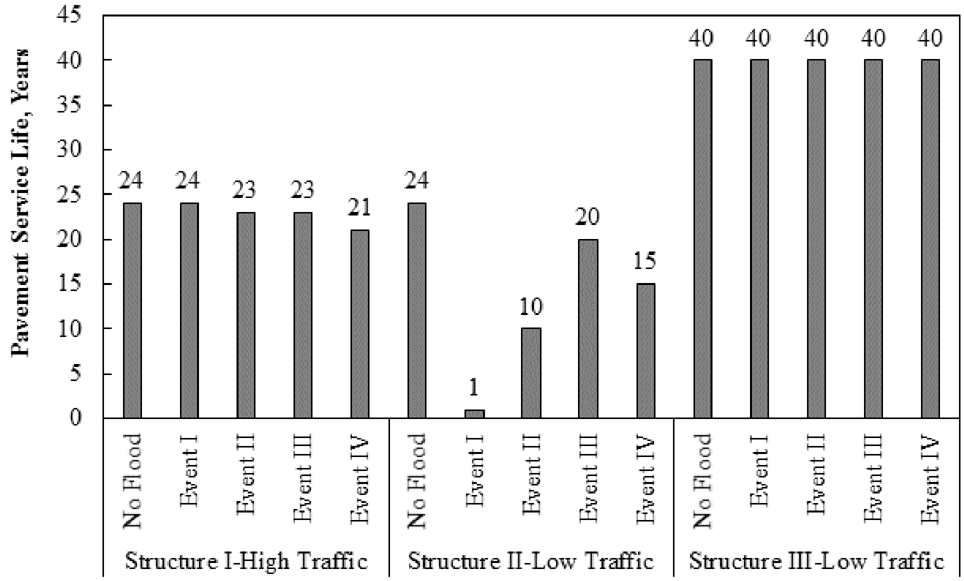

Figure 10-12. Summary of the simulation results for the three studied structures. (TXDOT)

The pavement impact analysis showed that Pavement Types 6 and 10 are prone to flood damage (specifically rutting) and may need to be reconstructed to the specifications of Pavement Type 5 (i.e., an asphalt concrete–surfaced pavement structure) to withstand future flooding events. There are approximately 110 state-maintained lane-miles of Pavement Type 6 and 10 in the TxDOT Houston District. However, almost 50% of the lane-miles (i.e., 53 lane miles) are at minimal risk of flooding. Since these Pavement Types represent a relatively small percentage of the Houston state-maintained network, the worst-case scenario, hardening all the Pavement Type 6 and 10 sections, will cost the agency $17.2 million.

Next steps

The data and methodologies outlined in this section of the report provide the agency with a framework to better assess the impacts of flooding on its state-maintained network. Although the pilot study focused primarily on the Houston District, the agency could use the same methods to assess the impacts of flooding events on the entire state's road network. The results could also be used to inform changes to TxDOT's pavement management system (Pavement Analyst), such as deterioration models and decision trees to select investment strategies in preparation for and in the aftermath of future flooding events.

Lessons learned

The pilot project reaffirmed that direct engagement of individuals with a wide range of expertise is essential for developing vulnerability assessments. Many of the data, models, and expertise for refining and mitigating flood risk already exist. As such, one of the challenges for transportation professionals is to incentivize experts in other fields to share data, models, and knowledge. The stakeholder meeting conducted at the beginning of this project sought to bring together a diverse set of stakeholders to identify key reciprocal interactions that could benefit all agencies involved in predicting and mitigating floods. For example, hydrologists charged with predicting flood events highlighted the importance of engaging with transportation engineers to better understand the influence of transportation infrastructure on flood risk. Other stakeholders noted the need for effective collaboration among transportation stakeholders and entities such as school districts or major industries to address travel restrictions caused by flooding events.

The TxDOT pilot project team also identified a number of challenges with the analysis, as well as opportunities to refine the methodology piloted in the project:

- **More robust tools are needed to simulate other impacts from flooding**. This pilot study evaluated the impact of flooding on pavement structures in terms of rutting. Besides rutting, water inundation can also lead to stripping of AC layers, creating the potholing affect often seen after heavy rain events. This phenomenon is not modeled in TxME, and its occurrence is difficult to simulate. A lack of robust models also prevented the evaluation of alternative measures (more frequent maintenance of culverts, improved drainage and hydrological solutions, adding shoulders, roadside vegetation/stabilization) on the pavement service life given a flooding event.
- **The LiDAR data and analyses could be modified to determine more accurately the profile of selected road infrastructure.** The study team could further analyze the road topography layer to explore the impacts of local topographic features on flood risk. The exploration and further improvements to the analyses presented in this study may be useful for transportation engineers to formulate hypotheses about the relationships between topography, roads and flooding.
- **The road topography data generated using LiDAR could be useful for extending the flood risk assessment methodology**. Combined with routing information and traffic volumes, road topography data could be used to explore interactions among traffic volumes using the roads following flooding and pavement damage. For example, it is possible that roads closed because of complete floodwater inundation are subject to less damage than those whose substructures become saturated, but remain open, and therefore experience normal traffic volumes, or increased traffic volumes as vehicles re-route due to other road closures. Similarly, the data may be useful to identify routes that are largely unaffected by inundation, but which contain sections of roads that flood rapidly. Such routes may present a safety concern or at least an inconvenience for travelers using those roads.

For more information

View the final report at https://www.fhwa.dot.gov/asset/pilot/tx.pdf