Synthesis of Approaches for Addressing Resilience in Project Development

U.S. Department of Transportation

Federal Highway Administration

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July 2017

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16. Abstract

This report synthesizes lessons learned and innovations from recent FHWA studies and pilots to help transportation agencies address changing climate conditions and extreme weather events at the asset level. The report is designed to provide needed information to a range of engineering disciplines to integrate climate considerations into transportation project development, including:

- Information on why, where, and how to integrate climate considerations into the project development process
- Basic, practical information in related disciplines such as climate science and economics
- Lessons learned for various engineering disciplines from project-level studies that address how to assess project exposure and vulnerability to climate change stressors, and how to evaluate and select appropriate adaptation strategies.

This report presents climate sensitivities, FHWA guidance, lessons learned, adaptation options, and knowledge gaps for four engineering disciplines: coastal hydraulics; riverine flooding; pavement and soils; and mechanical and electrical systems.

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1. Executive Summary

Practitioners can use climate change data to inform engineering assessments and design—to assess climate impacts to transportation assets and identify potential adaptation options. This report synthesizes lessons learned and innovations from a variety of recent FHWA studies and pilots to help transportation agencies address changing climate conditions and extreme weather events at the asset level. The report is designed to facilitate the integration of climate considerations into a range of transportation engineering design projects. Specifically, this report provides:

- Information on why, where, and how to integrate climate considerations into the project development process.
- Basic, how-to information in related disciplines such as climate science and economics.
- Lessons learned, climate sensitivities, FHWA guidance, adaptation options, and knowledge gaps for various engineering disciplines from project-level studies.

Recent weather events have shown that some assets are already extremely vulnerable to climate-related impacts; these vulnerabilities are likely to increase as the climate changes. In addition, State and Federal guidelines and requirements for addressing climate change impacts in transportation project design have increased in recent years. Engineering-informed adaptation studies, like those covered in this report, can help to meet these requirements and guidelines.

1.1. Integrating Climate Considerations

Projected climate change is anticipated to have significant impacts on a wide variety of transportation assets. For example:

- Sea level rise, storm surge, changes in coastal storm frequency and strength, changes in offshore wave heights, and coastal geomorphology threaten coastal infrastructure through impacts such as wave attack, bluff erosion, and overtopping.
- Changes in precipitation and the resulting changes in stream flows and flooding can flood travel lanes, wash out roadways, destabilize stream conditions, and aggrade channel beds in riverine environments.
- Changes in temperature, precipitation, and moisture, including changes in frost penetration, freeze-thaw cycles, wet-dry cycles, and groundwater levels threaten all parts of the pavement system, as well as soil and rock slopes, causing impacts such as rutting and cracking, smoothness deterioration, roadway deformation, and destabilized rock and soil slopes.
- Flooding, increased temperatures, and high winds threaten mechanical and electrical systems resulting in impacts such as short-circuiting, corrosion, service disruptions, and permanent damage.

Practitioners should consider climate change impacts and adaptation early in the project development process to ensure climate resilience is fully incorporated into the project design.

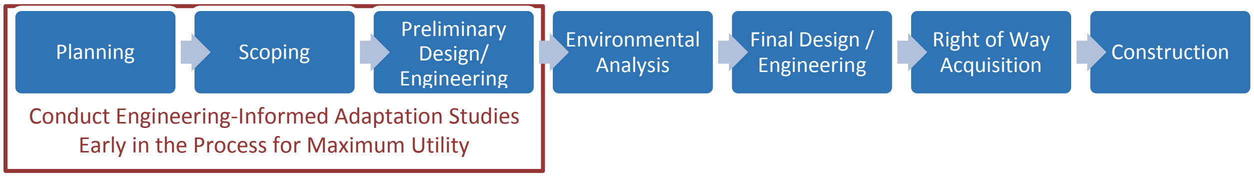

FIGURE 1: WHERE TO INTEGRATE CLIMATE CONSIDERATIONS IN THE PROJECT DEVELOPMENT PROCESS.

Several essential elements should be included in any adaptation study, as shown in Figure 1. Practitioners can use the information provided in this report to support each element of the study. Ultimately, by completing this process, practitioners will gain an understanding of how the asset under study is vulnerable to climate change, what adaptation measures will effectively increase resilience, and how to implement the selected measures.

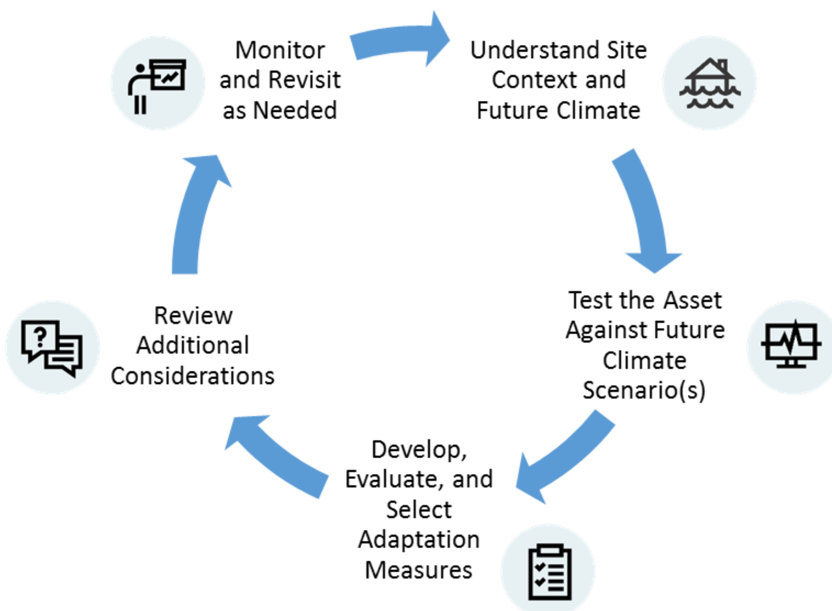

FIGURE 2: KEY ELEMENTS OF AN ENGINEERING-INFORMED ADAPTATION STUDY.

1.2. Using Climate Information

Engineers have well-established methods for analyzing historical records to make assumptions about the type of climate an asset will be exposed to over its lifetime. However, planning and designing for a future climate that is different than the past is less straightforward. While the same design standards and engineering equations may still be used, it is more difficult to make assumptions about what the future temperature, rainfall, flood levels, and other climate stressors might be given non-stationarity in the climate. Fortunately, there are several resources available for obtaining climate projection information as well as guidance on how to select and interpret future climate scenarios, models, and projections.

Practitioners can downscale projections for temperature and precipitation from the Downscaled CMIP3 and CMIP5 Climate and Hydrology Predictions (DCHP) website, which is FHWA's preferred source of climate data. Other well-vetted sources exist, as discussed in Section 4.1. Sea level rise projections are available from a number of different sources, including the U.S. Army Corps of Engineers (USACE) Sea Level Change Calculator. A few states have issued state-specific guidance, and some local communities have conducted detailed modeling at the local level.

FHWA's HEC-25 Vol. 2 and HEC-17 provide more detailed guidance on how to select scenarios, make decisions about models and timeframes, and adjust regional global projections so that they reflect local conditions.

There is uncertainty surrounding any climate projection data, due to scenario and scientific uncertainty, and natural variations in the climate system. However, there is also uncertainty in many of the other datasets used by transportation practitioners, so this should not be a deterrent from using climate projections. Instead, uncertainty in climate projections can be dealt with by considering a range of potential climate scenarios and model outputs.

1.3. Completing Engineering Assessments and Design

This report describes climate sensitivities, FHWA guidance, lessons learned, adaptation options, and knowledge gaps for four engineering disciplines:

- Coastal Hydraulics
- Riverine Flooding
- Pavement and Soils
- Mechanical and Electrical Systems

This report compiles numerous lessons learned across the four disciplines. Some themes recur across multiple disciplines and climate hazards:

- **Climate stressors often have non-linear effects.** For example, the effect of sea level rise on peak storm surge levels can be non-linear (i.e., future surge may be higher than the sum of today's surge levels and sea level rise), and peak storm flow response may not linearly follow precipitation trends forecasted by climate models.
- **Climate change does not necessarily mean design standards should change.** Design standards are set based on risk tolerance, which should not change over time. Rather, practitioners should consider how the design input necessary to meet the standard is shifting with climate change. For example, where a standard calls for withstanding the 100-year storm, practitioners should still design for the 100-year storm, but should recognize that the 100-year storm of the future may result in a larger streamflow, necessitating a different design.

- **Practitioners should consider both extreme *and incremental* changes.** For example, while floods may have more obvious impacts, gradual or incremental changes in temperature and precipitation will also have systematic and long-term adverse consequences on the performance of infrastructure (e.g., pavements) that warrant changes in preservation activities. However, while the cost premium for upgrades in design specifications may be low at a project level, since the effects will be systemic and statewide, the budgetary implications of adopting enhancements at the agency level warrants consideration. In general, practitioners must consider increases in the frequency of smaller, nuisance events in addition to extreme weather events.
- **It is important to consider the interactions among diverse climate stressors.** For example, wildfire burn of a watershed causes a dramatic increase in storm flows and creates the potential for debris flows. Similarly, practitioners should consider the relationship between the timing and nature of projected precipitation and temperatures when assessing climate change impacts on rock slope weathering, because freeze-thaw events that occur within a day or two of a precipitation event will have a more severe negative impact on slope stability.
- **In some cases, adaptation strategies will be very similar to existing practices.** For example, coastal climate adaptation measures for *roadways* will be similar to existing coastal engineering strategies for resilience (e.g., build "low and strong" or "high and dry").
- **Adaptive management can help manage uncertainty and reduce the risk of overspending.** For example, constructing a flood wall that can be heightened in the future, or taking an incremental approach to stabilizing landslides can help practitioners ensure that current investments provide value under a range of futures. With advanced planning, additional protection can be added as future climate conditions become more certain.

While adaptation strategies are specific to each engineering discipline, the categories of adaptation options are similar across disciplines:

- **Management and Maintenance:** Maintain existing infrastructure for optimal performance and manage the response to extreme events through advanced preparation.
- **Increased Redundancy:** Ensure that transportation services provided by infrastructure can be supplied by other alternatives.
- **Protection:** Reduce or eliminate damage by providing protective physical barriers to climate stressors.
- **Accommodation:** Modify or redesign infrastructure for better performance in a climate-stressed environment.

- **Relocation:** Lessen or eliminate exposure to climate stressors by relocating infrastructure away from the climate stressor.

Any of these strategies may include an adaptive design or adaptive management element, meaning they may be implemented step-wise over time, as needed.

1.4. Conducting Economic Analyses

Economic analyses can facilitate identification and selection of the most robust design, management, and adaptation scenarios. Economic analyses can range from fairly simple to highly complex; choosing the appropriate approach and cost estimation methods depend on resources available and the ultimate needs of the analyses, among other considerations.

There are several types of economic analyses used as part of the traditional transportation project development process, including: benefit-cost analysis, net present value, lifecycle cost analysis, and economic impact analysis. Economic analyses performed to identify efficient adaptation options can be considered enhancements of traditional lifecycle cost analyses. These enhanced analyses consider repair costs as well as socioeconomic; they also account for uncertainties or risks inherent in the assumptions of future climate scenarios. Different types of economic analyses may rank the preferred adaptation measures differently.

Lessons learned from the case studies on economic analysis of adaptation measures include:

- The discount rate selected can have a significant impact on the estimated dollar value of cumulative lifecycle benefits and costs. Conducting sensitivity testing around the discount rate can help to determine how it changes the results.
- Economic analyses of adaptation measures are greatly influenced by what is included within the bounds of the analysis. Generally, the broader system should be considered in the economic analysis of adaptation measures.
- Results of economic analyses of adaptation measures can vary greatly by asset and location.
- In some cases, adaptation options are easily justified economically. For example, coastal climate adaptation measures may be economically justified today in response to recent weather events; the economic justification for these measures will increase as sea levels rise. Similarly, the capital cost of culverts is a small fraction of the total lifecycle costs and therefore the incremental cost of a larger culvert will frequently be economically justifiable.

1.5. Evaluating Additional Considerations

It is important that practitioners consider additional factors when selecting adaptation options, including factors related to environment, economy, society, governance, broader environmental and transportation systems, and agency priorities. Layering these considerations into decision-making will provide a more complete understanding of the full value to the agency and community.

Additionally, considering the bigger picture can help practitioners identify when regional solutions may be more effective than asset-based interventions, and can ensure that "adaptation islands" are not created. An adaptation island could be created, for instance, if a bridge is adapted to future conditions but the approach roads are still vulnerable to flooding.

1.6. Monitoring and Revisiting as Needed

Once a course of action has been decided, a facility management plan should be developed to determine when to implement the adaptation measure and to ensure the project continues to perform as designed under changing climate conditions. In light of the uncertainty in future climate change projections, adaptive management may play an important role in ensuring the project is resilient. Phased adaptation strategies should be incorporated into an overall asset management strategy.

The performance of the facility and regional climate trends should be monitored after the project is constructed. It may be important to revisit the adaptation analysis and conclusions in the future for several reasons, including:

- Land use changes, demographic changes, and changes in mobility patterns may change the functional use of the asset.
- Climate projection data, including sea level rise, will improve over time.
- Advancements in engineering may make new adaptation measures feasible or lower the costs of others.

1.7. Ongoing FHWA Research

FHWA is continuing its research on incorporating engineering into climate resilience beyond the case studies reviewed in this report. These projects provide an opportunity to fill existing gaps, investigate topics in greater depth, and integrate information on new practices and data as they become available. Information and results of these projects will be posted on FHWA's Hydraulics Climate Change Website and Sustainable Transportation and Resilience Website.

2. Introduction

This chapter provides background information on FHWA's research on climate change and transportation, explains the purpose of the report, and presents an overview of the contents of the report.

2.1. Background

Over the last decade, FHWA has developed information on future risks to transportation infrastructure and services associated with extreme weather events and a changing climate. It has conducted or supported a number of studies that developed and/or tested methods for assessing vulnerabilities and identifying and evaluating adaptation measures. Initial efforts focused on understanding vulnerabilities at a larger geographic scale and developing processes to assess system-wide vulnerabilities, such as the *Climate Change and Extreme Weather Vulnerability Assessment Framework*, the *Gulf Coast Study* (Phase I and parts of Phase 2), and the first round of FHWA's Climate Change Resilience Pilot program.

As the knowledge base in this area of practice has grown, FHWA has begun to develop methods to support assessment of project-level risks and adaptation options (see box). This work includes:

- Development of decision-making frameworks that can serve as a resource for other transportation agencies conducting similar analyses.
- Pilot projects and case studies that examined specific assets, used different methods to determine if and how the assets could be affected by extreme weather events and changes in climate, and evaluated the cost-effectiveness of various adaptation measures.
- Technical guidance for addressing coastal and inland hydrological risks.

FHWA-Supported Asset-Level Assessments

Gulf Coast Study, Phase 2, Task 3.2 (2014)

2013–2015 Climate Change Resilience Projects

Hurricane Sandy Follow-up Vulnerability Assessment & Resilience Study (2017)

Transportation Engineering Approaches to Climate Resiliency (TEACR) (2016)

FHWA Engineering Manuals

HEC-17 (2016) Highways in the River Environment – Floodplains, Extreme Events, Risk, and Resilience

HEC-25 Vol 2 (2014) Highways in the Coastal Environment: Assessing Extreme Events

2.2. Purpose of This Report

Although many state and local transportation agencies recognize the need to make transportation assets more resilient, there are few methods and best practices they can draw on to determine which assets may be compromised under future conditions and how to evaluate and select adaptation measures. This report is an initial attempt to synthesize lessons learned from a wide-ranging set of studies and pilots (see box above) to help transportation agencies address concerns associated with changing climate conditions and extreme weather events during project-level scoping and to consider ramifications for design. Organized by engineering discipline, this report identifies key lessons that may assist other agencies when doing their own analyses, summarizes the adaptation strategies considered in various case studies, and includes information on remaining knowledge gaps. The lessons and processes are applicable to new, retrofitted, or replacement transportation infrastructure.

It is important to recognize that every transportation asset location is unique. Considerable care should be exercised in extrapolating the lessons learned directly to other situations or in assuming the lessons are representative of appropriate conclusions for national policy guidance. However, in this early stage of climate change and transportation engineering analysis, sharing lessons learned and developing a community of practice is a useful way to help transportation agencies prepare for climate change and extreme weather events.

2.3. Contents of the Report

This section provides an overview of the chapters of this report. The remainder of the report is organized as follows:

Chapter 3: Integrating Climate Considerations into the Transportation Project Development Process provides a brief overview of the project development process, how engineering-based adaptation studies could be incorporated into project development, and requirements and guidance for considering climate change during environmental review and project design. Chapter 3 then summarizes the core elements across various engineering-informed adaptation analysis frameworks developed and tested by FHWA since 2009.

Chapter 4: Using Climate Information. This chapter provides information for engineers on how to easily identify and collect information on climate change stressors that could affect the transportation asset.

Chapter 5: Completing Engineering Assessments and Design. Chapter 5 synthesizes lessons learned from various case studies that have conducted engineering-informed adaptation analyses. The chapter is organized by engineering discipline: coastal hydraulics, riverine flooding, pavement and soils, and mechanical and electrical systems. Chapter 5 also discusses key lessons learned that apply across engineering disciplines.

Chapter 6: Conducting Economic Analyses. Chapter 6 describes approaches to economic analyses to help select the most robust adaptation strategy.

Chapter 7: Evaluating Additional Considerations. Chapter 7 provides examples of a range of additional considerations, such as environmental, societal, and governance factors, that are important to making the right decision on a project.

Chapter 8: Monitoring and Revisiting as Needed. Chapter 8 outlines a few principles for development of a facility management plan to and describes the importance of revisiting the climate change and adaptation analysis in the future.

Chapter 9: Ongoing FHWA Research. Chapter 9 discusses the ongoing research FHWA is undertaking to advance the state of practice.

Appendices. The appendices contain a list of the case studies referenced in this report, a table of derived climate variables from the various case studies, a compilation of the lessons learned tables from throughout the report, and a glossary.

3. Integrating Climate Considerations into the Transportation Project Development Process

Before initiating design for a transportation project, planners and engineers conduct activities to fully develop the project concept. This transportation project development process is necessary to determine what issues are meaningful for consideration in the project design and to assess potential impacts of project alternatives. Several types of studies may be conducted to inform the process, such as a project planning or development study, corridor or feasibility studies, or a scoping study conducted before initiation of the environmental review process. These studies provide a way to assess and consider issues early so practitioners can avoid or minimize potential problems from the start.

This chapter provides a brief overview of:

- Where engineering-informed adaptation studies can be incorporated into the transportation project development process.
- The requirements and guidance for considering climate change in project development.
- The key elements of an engineering-informed adaptation study.

3.1. Where to Integrate Climate Change into the Project Development Process

Although the names may vary by state, the common phases of the transportation project development process are: planning, scoping[1], preliminary design/engineering, environmental analysis, final design/engineering, right-of-way acquisition, and construction. While these steps are presented in a linear fashion in Figure 3, communication and coordination among the various disciplines that work on the different steps in the process ensure that issues affecting project type, scope, development schedule, and costs can be correctly evaluated and anticipated. Furthermore, the process—if well-coordinated and well-managed—can reduce duplicated effort

It is important to consider climate change impacts and adaptation early in the project development process to ensure that climate resilience is incorporated into the project design to the extent possible and appropriate. It is during the first three stages—planning, scoping, and preliminary design/engineering—that engineering-informed adaptation studies can have the greatest impact on the design features of the project. In fact, the flexibility available for highway design during the final design phase is limited by the decisions made at the earlier stages of planning and project development. Additionally, the types of studies highlighted in this report are considered exploratory studies that would generally be conducted before the detailed environmental analysis done under state environmental regulations or under the

[1] Scoping in this context refers to general scoping activities that take place pursuant to project development, including activities prior to NEPA initiation, rather than scoping as formally defined in NEPA regulations at 40 CFR 1501.7.

federal National Environmental Policy Act (NEPA). Transportation practitioners can use the information generated to inform the remainder of the project development process.

The objectives of the **planning** and **scoping phases** respectively are to articulate the transportation system need that the project will address, and to determine the features that will allow the project to meet that need. Thus, the planning and scoping phases set the stage for project design. Consideration of climate change can inform decision-making to meet this objective. For example:

- Given future changes in climate, will the project be usable throughout its entire anticipated service life? If sea level rise will inundate the surrounding community then it may not be usable its entire planned service life, which would alter the perceived need for the project during the planning phase.
- Given future changes in climate, should increased resilience to extreme weather events be a consideration in project scoping? Identifying local climate change stressors that may influence the project design or feasibility is important to know early in the project development process.

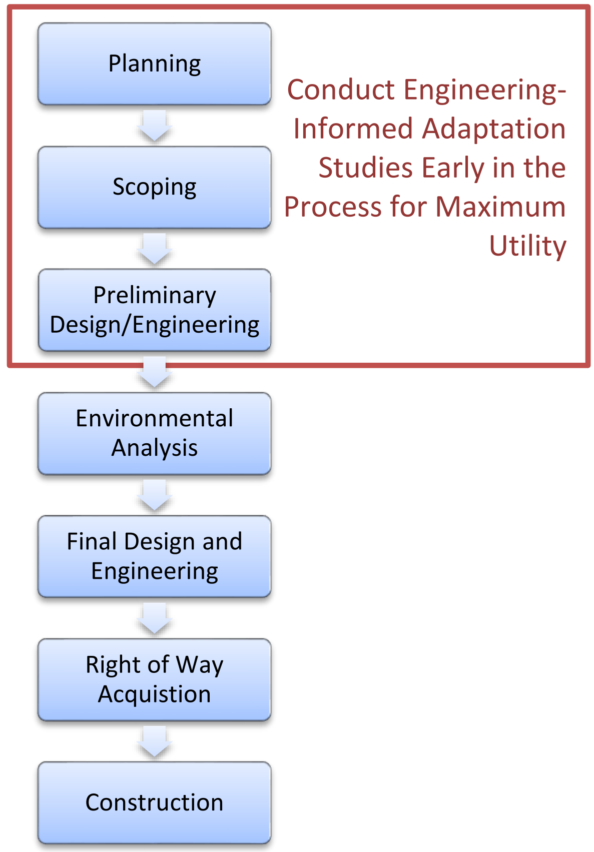

FIGURE 3: PROJECT DEVELOPMENT PROCESS.

Building upon the work completed in the planning and scoping phases, the general objective of the **preliminary design and engineering phase** is to begin the process of collecting more detailed information to inform the development of the project by conducting field investigations, other technical studies (e.g., environmental studies, climate change studies), and preliminary engineering studies. An engineering-informed adaptation study can add to the body of background knowledge that will inform subsequent phases of the project development process.

As noted above, the types of studies discussed in this report would optimally occur during the planning, scoping, and preliminary design/engineering phases of the project development process in order to maximize their value throughout the project development process.

Scaling the Level of Detail of Climate Change Assessments

Since projects generally require a level of scoping and preliminary design/engineering commensurate with the type of proposed work, the level of detail of the engineering-informed adaptation studies should also be scaled to the project at hand. In some cases, a non-engineering based climate vulnerability screening analysis for the transportation asset or system may be all that is needed (the FHWA Virtual Framework for Vulnerability Assessment provides more information on this type of screening). In other cases, such a screen would be simply a starting point to determine if and how the climate is projected to change, and more detailed engineering-informed study of what that means for the project in question would be necessary. This report focuses on those instances when a detailed engineering-informed study is necessary.

3.2. Why to Integrate Climate Change Considerations into Project Development

Engineering-informed adaptation studies, such as those covered in this report, can be an important part of addressing recent state and federal guidance and requirements for addressing climate change impacts in transportation project design. The following subsections provide a summary of the guidance and requirements to address climate change impacts during environmental review and project design.

3.2.1. State and Federal Environmental Review Regulations and Guidelines

State and federal (i.e., NEPA) environmental review processes establish a framework for transportation agencies to consider the potential environmental consequences of their proposals, document the analysis, and make this information available to the public for comment prior to implementation. In the transportation project development process, the environmental review phase occurs immediately after the preliminary design and engineering phase. If the engineering-informed adaptation studies are developed prior to undertaking the state or federal environmental review (as recommended above), the studies will help streamline and focus the environmental review on the issues identified as most important or significant. However, it is important to remember that 23 CFR §636.103 requires that "prior to completion of the NEPA review process, any such preliminary engineering and other activities and analyses must not materially affect the objective consideration of alternatives in the NEPA review process." In essence, the engineering-informed adaptation studies may help inform the environmental review alternatives but it should not bias the process by pre-determining a single course of action as the only feasible alternative.

Some state DOTs have begun to consider climate change impacts on the transportation asset in their environmental review documents. Washington State, in particular, has gone a step further and issued guidance that establishes how practitioners are expected to address climate change impacts in State Environmental Protection Act (SEPA) and NEPA documents.[2] The guidance includes climate change projection resources, guiding questions, an analysis checklist, and case study examples.

3.2.2. Other State and Local Regulations and Guidelines

Some states have requirements that climate change be considered in project scoping and design. The following bullets provide a summary of the requirements to date:

- Caltrans *Guidance on Incorporating Sea Level Rise: For use in the planning and development of Project Initiation Documents* (2011). In November 2008, Governor Arnold Schwarzenegger signed Executive Order (EO) S-13-08 directing state agencies planning construction projects in areas vulnerable to sea level rise to begin planning for potential impacts by considering a range of sea level rise scenarios. This guidance is intended for use by Caltrans planning staff and project development teams to determine whether and how to incorporate sea level rise concerns into the programming and design of Caltrans projects.
- Maryland *Climate Change and Coast Smart Construction Infrastructure Siting and Design Guidelines* (2015). In December 2012, Governor Martin O'Malley issued the Climate Change and "Coast Smart" Construction EO, which includes a number of policy directives to increase the resilience of the state's investments to sea level rise and coastal flooding. In response to the EO, Maryland developed these guidelines to provide "Coast Smart" construction guidance, including recommendations for the siting and design of state structures and infrastructure, institutionalization into state policies and programs, and technical tools and resources.
- Delaware *Avoiding and Minimizing Risk of Flood Damage to State Assets: A Guide for Delaware State Agencies* (2016). As mandated by Governor Jack Markell's EO 41: *Preparing Delaware for Emerging Climate Impacts and Seizing Economic Opportunities from Reducing Emissions,* this guidance provides state agencies with step-by-step instructions for avoiding and minimizing flood risk to state assets. The guidance and instructions aim to help state agencies ensure that flood risks— both existing flood risk and future risks posed by climate change—are considered during the planning and design of public buildings and infrastructure projects.
- Port Authority of New York and New Jersey *Design Guidelines: Climate Resilience* (2015). These guidelines provide guidance on how project designs should account for changes in temperature, precipitation, and sea level rise. It also provides step-by-step guidance on how to establish the flood protection criteria for a project.

3.2.3. Other Federal Regulations and Guidelines

In 2014, FHWA issued Order 5520 on *Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events*. Among other things, the order instructs FHWA to

[2] Washington DOT, 2017.

"encourage State DOTs, MPOs, Federal Land Management Agencies (FLMAs), tribal governments, and others to develop, prioritize, implement, and evaluate risk-based and cost-effective strategies to minimize climate and extreme weather risks and protect critical infrastructure using the best available science, technology, and information."[3] This report is one way in which FHWA is meeting the mandate of the order.

Chapter 2 of HEC-17 includes additional information on FHWA regulations, policy, and guidance on climate change and flooding.

3.3. How to Integrate Climate Considerations into Project Development

Although engineers already consider stressors from climate and weather when designing and maintaining infrastructure, risks associated with the nonstationary aspects of climate change have not historically been addressed in standard, well-established engineering design practices. Engineers have long incorporated flooding and other weather-related risks into designs; however, best practices for incorporating novel climate stressors, such as sea level rise, and/or weather extremes outside the bounds of historical records have not been established. Furthermore, different approaches for incorporating climate risks into design may materially impact workforce resource requirements. Thus far, guidance on matching resource-intensity of designs with desired design outcomes has been lacking.

FHWA acknowledges the evolving state of the practice in this area and has undertaken several efforts to inform the process and fill gaps engineers are facing in this area. FHWA sponsored engineering-informed adaptation analyses of a variety of transportation assets in different parts of the country. The purpose was two-fold: 1) to benefit the decision-making of transportation agencies in those jurisdictions, and 2) to glean lessons on analytical methods and adaptation strategies that could be useful elsewhere in the United States. Although the research teams used a variety of approaches, all of the approaches shared the same basic elements. The two primary processes followed include:

- The Adaptation Decision-making Assessment Process (ADAP), which was developed for the TEACR project. ADAP is a refined version of the 11-Step General Process for Transportation Facility Adaptation Assessments, which was developed for the Gulf Coast Phase 2 project.
- The FHWA Hurricane Sandy Follow-up and Vulnerability Assessment and Adaptation Analysis developed a module-based assessment process, which is anticipated to be posted online in fall 2017.

The rest of this chapter describes the key elements of these frameworks.

[3] FHWA, 2015b.

3.3.1. Key Elements of an Adaptation Study

While each of the frameworks developed and tested by FHWA have unique features, at their core, they share several key elements, which have been found to be essential through the testing and refinement of the various FHWA frameworks and engineering manuals. Figure 4 presents these key elements.

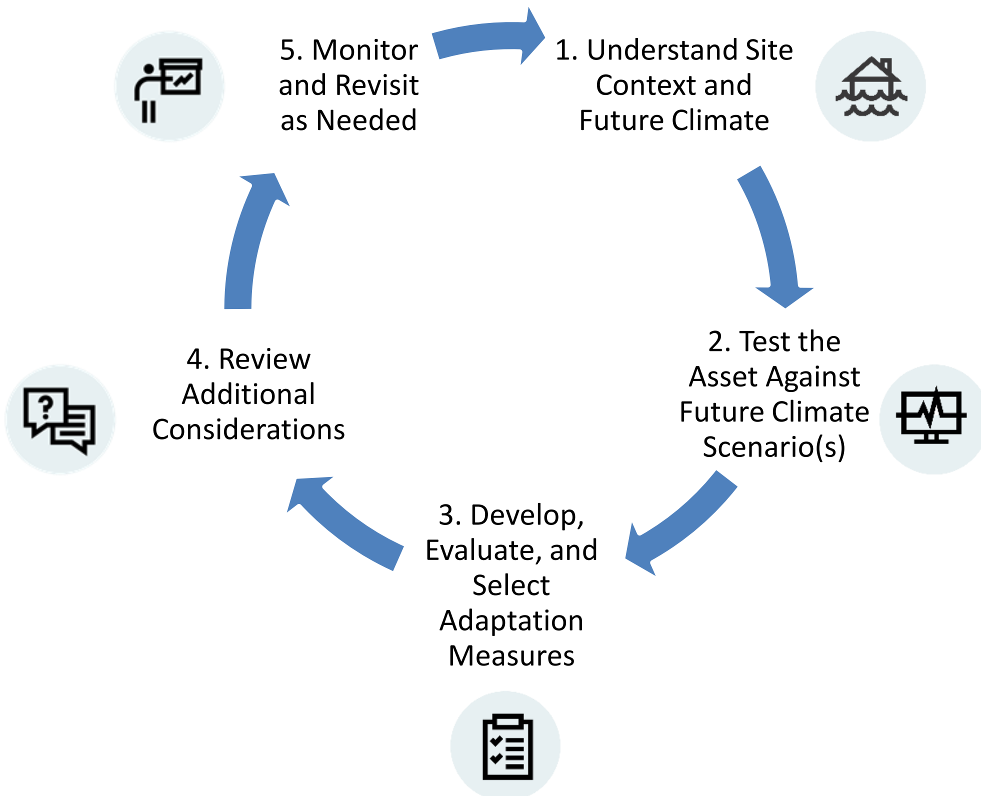

Figure 4: Key Elements of an Engineering-Informed Adaptation Study.

(1) Understand Site Context and Future Climate

Before embarking on an engineering-informed adaptation study, it is essential to understand both the context of the asset and the expectations of future climate conditions.

The context of a particular asset determines the appropriate scope and scale of the study. If the asset is vital to the operation of the transportation network, then the analysis may warrant more resources than if the asset provides redundant services and/or is nearing the end of its design life. In addition to informing the assessment of climate change impacts (Step 2), these

> **Examples of Site Context Considerations**
>
> - Asset design life and useful life
> - Function within the broader transportation network (e.g., how critical is the asset)
> - Location within the natural environment

contextual parameters will inform identification of adaptation measures in Step 3.

Starting with a basic understanding of how climate hazards (e.g., changes in precipitation and temperature, sea level rise, storm surges) may impact a given location and facility enables the practitioner to drill down, if necessary, and collect downscaled/localized data on the stressors that may impact the asset. Chapter 4 demystifies the potentially daunting process of assessing future climate for purposes of asset-specific studies and addresses concerns regarding uncertainty of climate projections.

(2) Test the Asset Against Future Climate Scenario(s)

Once projections of future climate are identified or developed, evaluate the asset (or proposed asset) to determine how it would perform under the projected climate change scenario(s). By undertaking an engineering-informed study, the practitioner will gain a better understanding of if, and how, the asset could be impacted. Chapter 5 discuss lessons learned from assessing impacts for different types of climate stressors.

(3) Develop, Evaluate, and Select Adaptation Measures

If the asset will be negatively impacted by climate change, identify plausible adaptation strategies, and then evaluate their efficacy under the future scenario(s). In addition to engineering feasibility, there are many other considerations when developing plausible adaptation strategies. For example, the useful life and planned rehabilitation schedule can impact whether the asset should be retrofitted now or during its next planned rehabilitation or replacement. Also, check with other local, state, and federal agencies to see if there are broader climate adaptation efforts being undertaken that may alter the need for site-specific adaptation.

Selecting the appropriate adaptation measure to implement may depend on both efficacy and cost, so an economic assessment may be warranted. An economic assessment should not only consider the upfront cost of the various adaptation options, but also the costs and benefits (i.e., economic pros and cons) of adaptation over the lifetime of the asset to help practitioners identify the most cost-effective options. Chapter 5 discuss lessons learned from evaluating adaptation measures, and Chapter 6 discusses methods for economic assessments.

(4) Review Additional Considerations

Asset-specific studies are necessary in the context of asset design, capital plans, retrofit cycles, and ongoing operations and maintenance efforts. However, it is important to consider how a specific asset contributes to the broader transportation network and relates to the environmental setting. For this reason, the final decision of the appropriate adaptation measure will include consideration of the surrounding environment, the future of the transportation system of which the asset is a part, and socioeconomic considerations as well. Budgetary (and political) considerations may also come into play. A robust discussion of additional considerations can be found in Chapter 7.

(5) Monitor & Revisit as Needed

The transportation system and surrounding communities are always changing. A decision that makes sense today may not be the best decision in the future. Furthermore, climate projections will continue to improve, reducing the uncertainties and easing the development of plausible scenarios. Therefore, engineering-informed adaptation studies are designed such that they can be revisited as the asset context and/or future climate conditions begin to change. Additional discussion of this topic is included in Chapter 8.

4. Using Climate Information

Engineers already consider stressors from climate and weather when designing and maintaining infrastructure. Local climate and weather patterns affect everything from how to size a culvert to which materials to use in pavement to how to protect assets from erosion. In the current state of practice, engineers draw from long records of historical data to make assumptions about the type of climate an asset will be exposed to over its lifetime. There are well-established methods for analyzing historical records, often resulting in a single numeric value to represent potential exposure. For example, historical data are used to generate estimates of flood heights for 4 percent, 2 percent, and 1 percent annual exceedance probability (25-, 50-, or 100-year events), which may provide the basis for how high to build a bridge or how large to build a culvert.

Historical vs. Projected Climate Data

Climate projection data differ from historical data. Historical data have been actually observed and measured. Projection data, on the other hand, are often generated by models based on assumptions of what the future climate might look like.

Implicit in the use of these data sets is the assumption of *stationarity*, or that historical weather conditions are indicative of future ones. However, climate change means that historical weather might not be indicative of future conditions—that is, the climate is nonstationary.

Thus, planning and designing for a future climate that is different than the past is not so straightforward. While the same design standards and engineering methods may still apply, it is more difficult to determine what the future temperature, rainfall, flood levels, and other climate stressors might be. Rather than simply looking at the historical record, engineers now are faced with multiple data sets developed based on different scenarios of future greenhouse gas levels, climate models, and timeframes. Moreover, climate projections do not always align with the data inputs engineers need, such as 30-minute duration precipitation data.

Fortunately, there are several sources of climate projection data that are publicly available, as well as FHWA technical guidance that give measured approaches to incorporating projections into designs. Although challenges still exist in incorporating climate information into designs—due mainly to issues of spatial and temporal scale (whereby data may not be available at an appropriate spatial or temporal resolution) and uncertainties associated with climate models, emissions scenarios and even hydrologic models—these challenges can be overcome, as discussed in this chapter.

This chapter discusses sources of climate projection information, background information on how the data sets were developed and what assumptions they are based on, and how to apply this information in engineering designs.

4.1. Sources of Climate Projections

There are several sources of publicly available climate projection information, meaning that transportation engineers do not need to start from scratch to develop necessary data. This section discusses the resources available for obtaining climate projection data, with a distinction between temperature/precipitation data and sea level rise projections, which are available from different sources.

It is important to note that climate science is continually evolving. The models, data sets, and other resources discussed throughout this chapter represent the best available knowledge at the time of publication of this report; in a few years, newer ones may be available. For example, new temperature and precipitation data will soon be available under the CMIP6 data set that is being developed.

4.1.1. Temperature and Precipitation Projections

Temperature and precipitation projections are often developed with the same climate models,[4] and thus are frequently available from the same climate projection resources. These projections are available from a number of publicly available resources, and come in the form of regional or downscaled projections. Regional projection information—such as from the U.S. Global Change Research Program (USGCRP)'s National Climate Assessment[5]—may be useful for a coarse screening of vulnerability, or for help framing a discussion about how the climate could change in the future.

However, although regional data sets are good for identifying general trends of concern, they do not capture site-specific conditions that are necessary to inform asset-level design, maintenance, and repair. Climate models produce climate projections at a coarse geographic scale—generally more than a hundred miles on a side—which is often far too coarse for project-level analyses. *Downscaling* is a process used to refine the resolution of climate projections so that they better reflect local conditions. See Section 4.2.1.3 for more information on downscaling techniques and sources of downscaled data sets.

Downscaled climate projection data are commonly used when conducting project-level work. All case studies referenced in this report used downscaled data sets.

Transportation engineers generally do not need to develop downscaled climate projections on their own—there are several sources of publicly available, readily downloadable data sets from which to draw. As noted in HEC-17 Chapter 5, FHWA recommends the following data clearinghouses of downscaled climate projections:

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[4] See Section 4.2.1 for more information on how temperature and precipitation projections are developed.

[5] Melillo et al., 2014.

- Downscaled CMIP3 and CMIP5 Climate and Hydrology Predictions (DCHP) database, which is FHWA's preferred source of projection data (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html)
- USGS Geo Data Portal (http://cida.usgs.gov/gdp/)
- Coordinated Regional Climate Downscaling Experiment (CORDEX) (https://na-cordex.org)
- North American Regional Climate Change Assessment Program (NARCCAP) (http://www.narccap.ucar.edu/)

These resources are discussed in the subsections that follow.

4.1.1.1. DCHP Database

FHWA recommends use of two of the downscaled CMIP5 data sets (LOCA or BCCA) available from the DCHP database. The DCHP database includes projections for multiple scenarios and models covering the contiguous United States, and uses statistical downscaling techniques. FHWA's CMIP Climate Data Processing Tool simplifies the process for obtaining and processing the data. FHWA prefers this database because the data sets are easily accessible and downloadable, enabling users to obtain data for multiple emissions scenarios and climate models at scales as detailed as 1/16 degree by 1/16 degree, or roughly 4 miles by 4 miles (6 km by 6 km) at mid-latitudes.

FHWA also has confidence in the quality of the data, noting that DCHP is supported by several federal agencies and nongovernmental groups focused on climate change research, including the USACE, the US Geological Survey (USGS), Department of Energy (DOE), Bureau of Reclamation, and the National Center for Atmospheric Research (NCAR).

The DCHP database contains downscaled data from both the third and fifth phase of the Coupled Modeled Intercomparison Project—data sets traditionally referred to as CMIP3 and CMIP5. See Chapter 5 of HEC-17 for a summary of these different data sets. It is expected that CMIP6 data will be added to this database in the next few years.

4.1.1.2. Other Sources

Though FHWA prefers the DCHP database, there are other reputable sources for climate projection data that could be used. These sources include:

- USGS Geo Data Portal, which includes statistically downscaled data from a variety of sources (including the BCCA data set also hosted through the DCHP database)
- NA-CORDEX website, which contains links to dynamically downscaled data sets for North America
- NARCCAP website, which contains dynamically downscaled data sets based specifically on the (slightly dated) Special Report on Emissions Scenarios (SRES) A2 emission scenario (see section 4.2.1.1 for more information)

These sources of data use downscaling techniques that may make them more useful than the DCHP database for certain projects, particularly when conducting HEC-17 Level 5 analyses. For example, the USGS Geo Data Portal and the NA-CORDEX website include some dynamically downscaled data sets for the U.S. Pacific Islands, southwestern United States, and the Pacific Northwest.

4.1.2. Sea Level Rise Projections

Selecting appropriate sea level rise scenarios is different than selecting temperature and precipitation projections. Transportation practitioners generally need to determine the relevant range of global sea level rise estimates, and then obtain or develop data sets that adjust global estimates for local land uplift or subsidence to understand local sea level rise. Other geomorphologic processes like erosion are sometimes also considered to get a fuller understanding of the exposure of transportation assets to sea level rise. See Section 4.2.2.1 of this report, and HEC-25 Vol 2 Section 2.3.1, for more information on sea level rise and FHWA's guidance on estimating relative sea level rise.

Some data sets exist that already adjust global estimates for local uplift and subsidence, such as the first four listed below. In some situations, however, transportation engineers may need to develop their own estimates, particularly in areas where relative sea level rise rates are not available, or in situations where it is important to account for a fuller picture of local coastal geomorphologic processes.

Some potential sources of sea level scenario information are:

- The USACE Sea-Level Change Curve Calculator
- State or local guidance on appropriate sea level rise scenarios, such as the California Department of Transportation's Guidance on Incorporating Sea Level Rise
- The National Oceanic and Atmospheric Administration (NOAA)'s Technical Report NOS CO-OPS 083: Global and Regional Sea Level Rise Scenarios for the United States
- The National Research Council's *Sea-Level Rise for the Coasts of California, Oregon, and Washington*
- The National Climate Assessment's Climate Change Impacts in the United States

These resources are described in the subsections that follow. Figure 5 shows the sea level rise scenarios included in these resources.

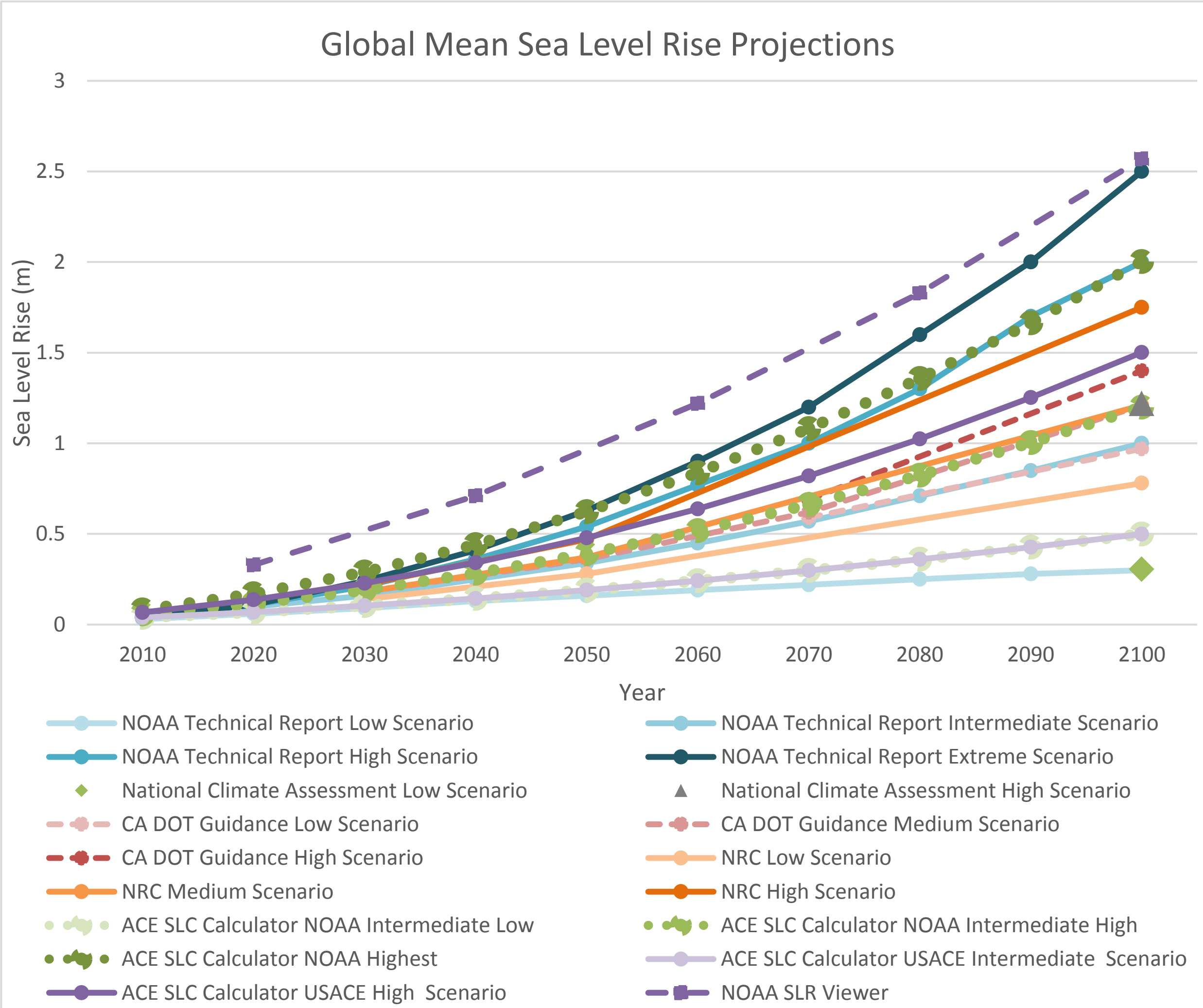

FIGURE 5: GLOBAL SEA LEVEL RISE SCENARIOS FROM RESOURCES MENTIONED IN THIS CHAPTER.

4.1.2.1. State Sea Level Rise Guidance and Local-Level Data Sets

A small number of states have released statewide guidance on selecting and applying sea level rise scenarios. Where applicable, engineers should use this State-issued guidance. The State guidance documents include:

- The State of California Sea-Level Rise Guidance Document, last updated in 2013 but currently undergoing another update expected to be released in January 2018 by the

California Ocean Protection Council.[6] This document contains recommended sea level rise scenarios and guidance on how to use them in project-level analyses. The California Department of Transportation (Caltrans) companion document, Guidance on Incorporating Sea Level Rise, includes more specific guidance on incorporating the Ocean Protection Council's recommendations into transportation projects. Meanwhile, sea level rise data for some areas can be downloaded from the state's Cal-Adapt website, although additional site-specific analysis may still be needed to conduct an engineering analysis.

- Massachusetts's Sea Level Rise: Understanding and Applying Trends and Future Scenarios for Analysis and Planning was released in late 2013 and provides general guidance from the state on selecting and applying sea level rise scenarios.
- Though not statewide guidance, the Southeast Florida Regional Climate Change Collaborative's Unified Sea Level Projection: Southeast Florida provides projected sea level rise for the southeastern part of the state through 2100 that accounts for local subsidence and other factors. This document also includes guidance on how to select the appropriate scenarios.

In addition to determining sea level rise scenarios, transportation engineers must determine how sea level rise will affect flood frequency at a project site based on factors like elevation and hydrological connectivity. Many local entities throughout the United States have conducted their own sea level rise studies that capture these features. These studies might have resulted in detailed and quality data sets that transportation practitioners could use for their own projects, thereby saving considerable resources when obtaining sea level rise projection information. Even if the data sets cannot be used for the engineering analysis at hand, transportation practitioners might want to use similar scenarios, data sources, or assumptions to provide consistency with other local projects. Therefore, it is worth considering whether other entities have conducted sea level rise assessments in the area prior to commencing an engineering analysis.

4.1.2.2. USACE Sea Level Change Calculator

If no State guidance is provided, FHWA recommends using the USACE Sea Level Change Calculator. This calculator adjusts a range of global sea level rise estimates for localized vertical land movement (or the nearest NOAA tide gage) through 2100. Using historical NOAA tide gage data, local subsidence/uplift rates, and sea level rise estimates based on the National Research Council (NRC), Intergovernmental Panel on Climate Change (IPCC), and NOAA, this calculator projects sea level rise over time for a high, medium, and low scenario. The calculator results are

[6] At the time of this report's publication, the updated sea level rise guidance was not available. However, California's Ocean Protection Council has issued an update to the climate science that will provide the foundation for the guidance. This update is called *Rising Seas in California: An updated on Sea-Level Rise Science,* and is available at http://www.opc.ca.gov/webmaster/ftp/pdf/docs/rising-seas-in-california-an-update-on-sea-level-rise-science.pdf.

presented based on both NOAA and USACE curves. In general, FHWA recommends using the NOAA curves.

4.1.2.3. NOAA Resources

NOAA Technical Report NOS CO-OPS 083: Global and Regional Sea Level Rise Scenarios for the United States

Released in January 2017, this report includes updated estimates on reasonable ranges for global mean sea level rise in ten-year increments through 2100, and also includes estimates for longer increments through 2200.

The report includes six different scenarios, ranging from 0.3 to 2.5 meters by 2100. It also indicates the probability that each of these scenarios could be reached under Representative Concentration Pathways (RCPs) 2.6, 4.5, and 8.5.

This report also contains some information on how these global changes in sea level would manifest at regional levels.

Sea Level Rise Viewer

The Sea Level Rise Viewer is a mapping tool that helps visualize community-level impacts from sea level rise. Users can visualize the exposure of sea level rise at different increments up to 6 feet of global sea level rise. It is a little different than some of the other sources mentioned in this chapter in that it is a tool that applies sea level rise projections in a spatial visualization tool, thus helping users see areas that could actually be exposed.

However, this tool does not account for erosion, subsidence, or other processes. Therefore, it is meant for educational purposes only, and is specifically not recommended for detailed site analyses. Still, it can be useful for determining areas that could potentially be more exposed, or the potential extent of inundation. It can be used as a screening tool to decide which areas warrant a closer look, although a more detailed sea level rise exposure analysis would be necessary to conduct the engineering analyses described in this report.

The Sea Level Rise Viewer is one of several tools, data sets, trainings, and other resources housed on NOAA's Digital Coast website.

4.1.2.4. National Research Council's Sea Level Rise for the Coasts of California, Oregon, and Washington

Although California has more updated resources for sea level rise as noted above, this resource may still be useful for Oregon and Washington. This report contains estimates for 2030, 2050, and 2100 and takes into account the geomorphologic processes that can affect relative sea level rise at the local level.

4.1.2.5. National Climate Assessment Projections

The U.S. Global Climate Change Research Program periodically updates their National Climate Assessments. The most recent assessment as of the publication of this report is Climate Change

Impacts in the United States: The Third National Climate Assessment, published in 2014. However, the fourth assessment is underway, with anticipated completion in 2018.

The Third National Climate Assessment contains information on the rate of global and regional sea level rise, including both historical and projected changes. As shown in Figure 6 below, the National Climate Assessment considers 1 to 4 feet to be a reasonable estimate range for future sea level rise, although risk assessments might consider a broader range of up to 0.66 to 6.6 feet.[7]

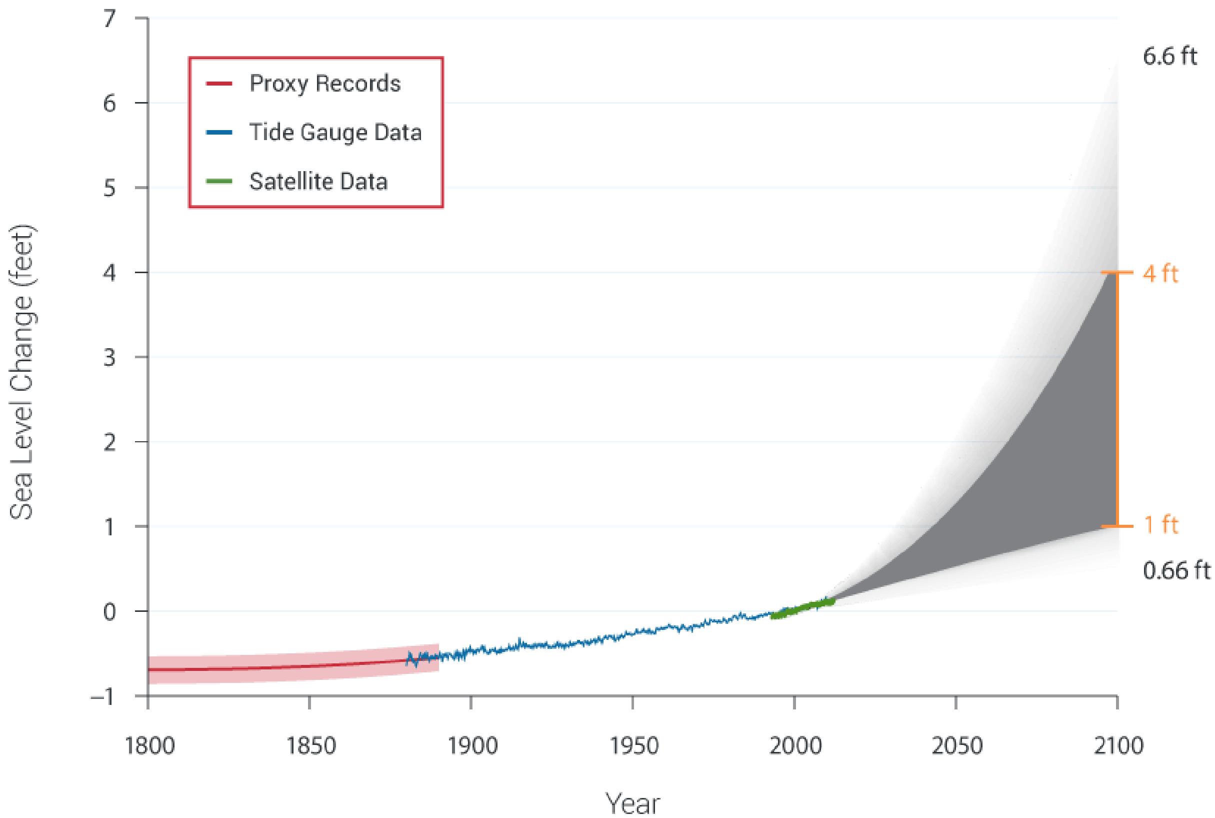

FIGURE 6: NCA GLOBAL SEA LEVEL RISE SCENARIOS.

Source: Walsh et al., 2014 citing Parris, 2012.

4.1.3. Summary of Sources for Climate Projection Information and Guidance

Table 1 summarizes the reputable resources for data and guidance when developing climate projections.

[7] Melillo et al., 2014.

Table 1: Sources for Climate Inputs and Guidance

Resource	Description	Climate Stressor
Data Sources		
Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections (DCHP) database http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html	• Contains publicly available, downloadable, downscaled climate projection data for the contiguous United States • FHWA's preferred data source for temperature and precipitation projections	Temperature; Precipitation
USGS Geo Data Portal https://cida.usgs.gov/gdp/	• Web portal provides access to a suite of climate data sets, including climate projections using different downscaling techniques	Temperature; Precipitation
U.S. DOT CMIP Climate Data Processing Tool http://www.fhwa.dot.gov/environment/climate_change/adaptation/publications_and_tools/	• Excel-based tool to process data from the DCHP database to provide projections for climate variables relevant to transportation planners (e.g., number of days above 95°F, hottest seven-day temperatures, largest three-day precipitation events) • Local-scale (56-224 sq. miles)	Temperature; Precipitation
U.S. Army Corps Sea Level Change Curve Calculator http://www.corpsclimate.us/ccaceslcurves.cfm	• A web-based tool that accepts user input to produce a table and graph of the projected sea level changes at the project site. Includes vertical land movement	Sea Level Rise
NOAA Technical Report NOS CO-OPS 083: Global and Regional Sea Level Rise Scenarios for the United States https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf	• Identifies reasonable ranges for global mean sea level rise through 2200 • Six different scenarios, plus probability that each could be reached under RCPs 2.6, 4.5, and 8.5	Sea Level Rise
National Oceanic and Atmospheric Administration's Sea Level Rise Viewer https://coast.noaa.gov/digitalcoast/tools/slr	• Web mapping tool to visualize community-level impacts from coastal flooding or sea level rise • Contains downloadable sea level rise data for many locations	Sea Level Rise

Resource	Description	Climate Stressor
National Research Council's Sea-Level Rise for the Coasts of California, Oregon, and Washington https://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington	• Contains projection information for California, Oregon, and Washington • May not be the most up-to-date resources for California, but a useful resource for Oregon and Washington	Sea Level Rise
National Climate Assessment http://nca2014.globalchange.gov/	• High-level descriptions of how climate stressors may change • Focused on larger geographic areas (e.g., Pacific Northwest, Southwest, Southeast) • Good starting point to identify what types of climate changes are expected in the region	All
Guidance		
FHWA HEC-17, 2nd Edition https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf	• Provides technical guidance and methods for determining vulnerability to extreme events and climate change in riverine environments • Includes information on accessing and interpreting temperature and precipitation projections	Temperature; Precipitation
FHWA HEC-25 Vol 2 http://www.fhwa.dot.gov/engineering/hydraulics/pubs/nhi14006/nhi14006.pdf	• Provides technical guidance and methods for determining vulnerability to sea level rise and storms in coastal environments • Includes a methodology for determining local sea level rise and modeling storm surge	Sea Level Rise; Storm Surge
U.S. Army Corps Engineering & Construction Bulletin No. 2016-25 http://www.iwr.usace.army.mil/Portals/70/docs/frmp/eo11988/ECB_2016_25.pdf	• Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects	Precipitation
U.S. Army Corps Engineering & Construction Bulletin No. 2016-05 https://www.wbdg.org/ffc/dod/engineering-and-construction-bulletins-ecb/usace-ecb-2016-05	• Guidance for Using Non-NOAA Tide Gage Records for Computing Relative Sea Level Change	Sea Level Rise
Partner Organizations		

Resource	Description	Climate Stressor
State climatologist	• May have already developed projections of how climate may change in the state/region	All
University climate research centers in the region	• May have already developed projections of how climate may change in the state/region	All
NOAA's Regional Integrated Sciences and Assessments (RISA) research teams http://cpo.noaa.gov/ClimateDivisions/ClimateandSocietalInteractions/RISAProgram.aspx	• RISA teams have a regional focus and bring together public and private entities to advance knowledge on, and build capacity to adapt to, climate change • Products and research priorities vary by region, but may include resources to visualize and learn more about regional impacts • RISAs can help transportation practitioners connect to climate change experts	All
USGS Climate Science Centers https://nccwsc.usgs.gov/csc	• Eight Centers each cover different regions of the U.S. • The Centers offer on-the-ground support and research related to climate change	All
Federal research agencies	• USACE, NOAA, USGS, EPA, USGS, NASA all maintain active climate change research groups	All

4.2. Developing Climate Projections

Climate projections are developed using models based on various assumptions, such as assumptions of future concentrations of greenhouse gas emissions. Model outputs are often adjusted to better account for local characteristics. This section discusses the process of developing projections, organized by temperature/precipitation and sea level rise/ storm surge projections, which are developed using different approaches. This section discusses the selection of scenarios, different models used, and how broader projections are then adjusted for local characteristics.

4.2.1. Developing Temperature and Precipitation Projections

To assess climate change impacts at the asset level, it is necessary to look at locally specific climate change projections. This involves considering appropriate: (1) climate scenarios, (2) models, and (3) downscaling, which are discussed in the subsections below. The final subsection discusses the uncertainty surrounding climate projection data.

Refer to HEC-17 Chapter 5 for more detailed discussion of scenarios, models, and downscaling.

4.2.1.1. Scenarios

It is impossible to predict precisely what the climate will look like in the future, as there are unknowns regarding greenhouse gas emissions and concentrations, and scientific uncertainty about how some climate processes function (see Section 4.2.1.4). Therefore, climate change is often discussed in terms of plausible futures or scenarios that are built on different trajectories of future greenhouse gas concentrations, land use, and other factors.

In 2013, the IPCC released new scenarios called RCPs[8] (see Table 2 and Figure 7[9]). The RCPs are based on a range of potential future rates of such factors as economic growth, population, and energy consumption that are translated into emissions and concentrations of greenhouse gases (GHGs) over time that are then run through climate models to project future values of temperature and precipitation. This table summarizes GHG concentrations and temperature for the RCP scenarios in 2100, and also compares emission rates for each scenario to actual 2010 levels, which provides insight on which scenarios are more likely to take place. RCPs are meant to take the place of the earlier scenarios presented in IPCC's SRES. FHWA recommends the use of RCPs over SRES; however, several case studies referenced in this report used SRES scenarios, usually because the case studies commenced prior to release of the RCPs. The total radiative forcing—that is, the capacity of these greenhouse gas concentrations to contribute to climate change—is shown graphically in Figure 7.

TABLE 2: REPRESENTATIVE CONCENTRATION PATHWAYS[10]

Scenario Name	Description	Concentrations (ppm CO_2 equiv.) by 2100	Global Surface Temp. Change by 2100*
RCP 2.6	Emissions reduced substantially from current pathway.	430–480	0.5–3.0 °F (0.3–1.7 °C)
RCP 4.5	Emissions reduced sufficiently so that total radiative forcing is stabilized by 2100.	580–720	2.0–4.7 °F (1.1–2.6 °C)
RCP 6.0	Emissions reduced sufficiently so that total radiative forcing is stabilized by 2100.	720–1,000	2.5–5.6 °F (1.4–3.1 °C)
RCP 8.5	High emissions continue through 2100. Most representative RCP of current emissions track.	>1,000	4.7–8.6 °F (2.6–4.8 °C)

[8] IPCC, 2017 citing Van Vuuren et al., 2011.
[9] IPCC, 2017 citing Van Vuuren et al., 2011.
[10] IPCC, 2014. For comparison, CO_2 concentrations have risen steadily since the dawn of the industrial revolution; concentrations have risen from 280 ppm in 1800 to more than 400 ppm in 2016. See: https://www.acs.org/content/acs/en/climatescience/greenhousegases/industrialrevolution.html; https://www.esrl.noaa.gov/gmd/ccgg/trends/full.html.

* Note that changes in global temperatures can mask more significant changes at a regional or local level. Also, an increase of 2 degrees Celsius above pre-industrial levels would bring average global temperatures to levels not experienced on Earth in millions of years. As noted in Carlowicz (n.d.),[11] "A one-degree *global* change is significant because it takes a vast amount of heat to warm all the oceans, atmosphere, and land by that much. In the past, a one- to two-degree drop was all it took to plunge the Earth into the Little Ice Age."

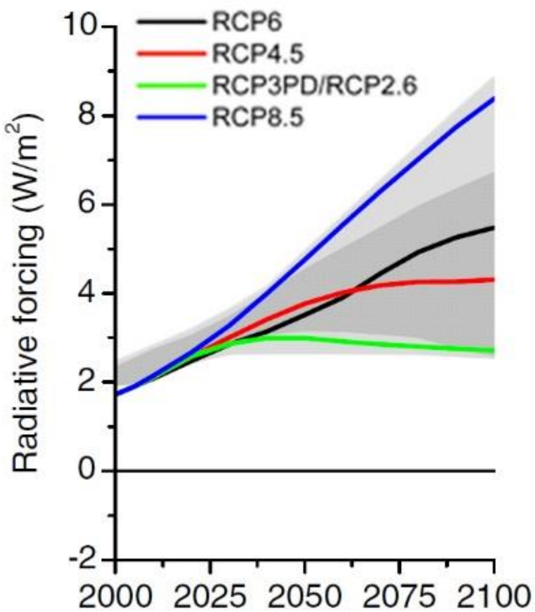

FIGURE 7: RADIATIVE FORCING OF IPCC RCPS.

Source: van Vuuren et al, 2011.

Uncertainty Across Timeframes

The spread of projections coming out of different climate models will be fairly small in the near term, but increase the further they go in time. Thus, it may not be necessary to spend resources to select the "right" model or models if the interest is in more near-term climate changes; their projected results are likely to be similar. However, if practitioners are concerned about climate changes in the long-term, it is more important to look at a range of models.

Although there are no strict rules on which scenario should be used for which situations, users are encouraged to consider the following:

- The selection of one RCP over another matters less for the near term because GHG concentrations do not diverge significantly when looking out just a few decades. However, when considering longer time frames where the concentrations diverge, RCP selection matters more.
- The lowest scenario (RCP 2.6) generally should be avoided as it is overly optimistic compared to recent emissions trends. Because GHGs are long-lived pollutants, concentrations change much more slowly than emission rates, and it would take a large drop in emissions to begin to approach the concentrations of this scenario.
- Whenever possible, practitioners should use a range of scenarios (choosing among RCPs 4.5, 6.0, and 8.5), and attempt to make decisions that are robust across those scenarios.
  - RCP 4.5 and RCP 6.0 exhibit similar GHG concentrations over the near- and medium-term (out to around 2060), meaning choosing between these RCPs will

[11] Carlowicz, n.d.

likely result in only minor differences when looking out to about 2060. After about 2060, however, RCP 6.0 exhibits higher concentrations. Thus, analyses that look at long-lived assets should give more consideration to whether RCP 6.0 or 4.5 (or both) is appropriate. Note that RCP 6.0 is recommended for use in HEC-17.
  - However, selection of RCP 4.5 allows for datasets from a broader range of models than for RCP 6.0. For instances where a broader range of models is desired, RCP 4.5 may be preferable to 6.0 for the near- or medium-terms.
  - For critical or long-lived assets (greater than 30 years), the highest scenario, RCP 8.5, should be strongly considered for one of the selected RCPs. GHG concentrations for this RCP are notably higher than for the other RCPs in the long-term. However, it should not be considered an extreme scenario. This highest RCP is clearly within the realm of the possible given that emissions rates have trended toward the high end of the RCP scenarios.[12]
  - RCP 8.5, like RCP 4.5, allows for datasets from a broader range of models than for RCP 6.0. In general, choosing a broader range of models allows for conducting a more robust analysis, although the more limited model range of RCP 6.0 is sufficient for many analyses.
- For more information on FHWA's recommendations, practitioners may consult HEC-17, Chapter 7.3: Downscaled Climate Data.[13]

Looking at a range of RCP scenarios provides a more informed perspective on the range of possible outcomes compared to using a single scenario, so transportation practitioners are encouraged to consider multiple RCP scenarios.[14] However, users should not average projections across scenarios. They should be viewed as distinct, potential future scenarios.

For all RCPs, the temperatures tend to increase as time goes on. For precipitation, however, trends are not always linear depending on location, RCPs, model, and other assumptions. For example, precipitation might increase in the short term, decrease in the medium term, and then increase again in the long term. If climate data indicate that precipitation might decrease, it is important to design infrastructure such as culverts and other drainage assets for *today's* climate rather than assuming drier conditions, which could increase risk in the present day.

Table 3 shows the emissions scenarios used in the case studies referenced in this report. It is worth noting that none of the case studies used the lowest RCP (2.6). In general, the case studies used a range of scenarios, with a slight emphasis on the higher scenarios. SRES scenarios appear in some of the earlier case studies.

[12] Melillo et al., 2014. Page 759.
[13] FHWA, 2016b.
[14] If three scenarios are selected, it is important to communicate that the middle scenario is not considered more likely than the other scenarios. It is often tempting to view a middle scenario as a more likely one and ignore the lower and higher ones, which is not an appropriate way to view the RCPs.

TABLE 3: EMISSIONS SCENARIO SELECTION ACROSS PROJECTS

Study	Climate Scenarios
TEACR	RCP 4.5, 6.0, 8.5
Gulf Coast Phase 2	SRES B1, A2, A1FI
FHWA Pilots, Phase 2	RCP 4.5, 6.0 and 8.5 SRES B1, A2, A1B, A1FI
Post-Sandy Recovery	RCP 4.5, 8.5

4.2.1.2. Global Climate Models

Climate models are complex numerical models used to examine the interactions between the atmosphere, land surface, oceans, and sea ice, and estimate future climate conditions based on these analyses.

There are dozens of climate models that could be used as sources of information about future climate change, and results can vary across models. For situations where an analysis is focused on high-value, critical assets with a long remaining design life, it may be prudent to include climate science experts on the design team who may recommend a targeted subset of climate models that are best suited to the given location and data need. This approach would be analogous to a Level 5 analysis in HEC-17 (see Section 5.3.2). Practitioners may want to consult with climate scientists in a NOAA Regional Integrated Sciences and Assessments (RISA) team, at a local university, with a state climatologist, or other experts.

In absence of expert guidance, however, FHWA recommends considering the full range of climate models available for each scenario considered, as noted in the U.S. DOT CMIP Climate Data Processing Tool User Guide.[15] No single model should be given more weight than any other model unless advised by an expert.[16]

Although it may be tempting to simply average all the model outputs to obtain a single set of values to work with, averaging can mute the range of possible future climate conditions. The scientific community often does not indicate preference for one climate model over another, and therefore it is difficult to say that the mid-point of a range is more likely than any other point along that range. Thus, in instances where model outputs are significantly different, it is

[15] USDOT, 2016.

[16] An exception is in Alaska, where certain models improperly represent historic and future conditions so care should be given to select appropriate models. For more information on scenarios that are appropriate for Alaska, consult with the Scenarios Network for Alaska + Arctic Planning group (SNAP) (https://www.snap.uaf.edu/). In addition, as the science advances, the understanding of the relative usefulness of different climate models is increasing. Therefore, in the future, it is likely that the general guidance to not weight climate models preferentially will change.

often better to consider both the higher and lower ends of the data range, to put bounds on the plausible futures.

It is important to remember that climate models are not meant to be used as *weather* forecasting models; that is the model results will not accurately predict the high temperature on a particular day in the future. See Section 4.2.1.4 for more information about the uncertainty surrounding the projection information.

Finally, climate projections data sets are not static; the climate science community continues to refine and run climate models and develop new downscaling techniques. For example, scientists are currently working on developing the next round of climate projections, CMIP6, while also updating downscaling techniques. UCAR is also developing data sets for Alaska and Hawaii.[17]

4.2.1.3. Downscaling

As noted in Section 4.1.1, climate models produce projections at a coarse geographic resolution, generally at a scale of over a hundred miles per grid cell side. This information is often too coarse to capture the site-specific conditions that are needed to inform asset-level analyses. For example, within a large geographic area, precipitation could be projected to increase substantially in one place and not increase in another (e.g., on opposite sides of a mountain range), leading the regional projection to indicate an average change that is not reflective of either site. Thus, the data need to be *downscaled* to a finer resolution.

There are two primary methods of downscaling: statistical and dynamical. Statistical downscaling considers the statistical relationship between local weather variables (e.g., surface rainfall) and larger-scale climate variables (e.g., atmospheric pressure); then, using that relationship, the climate model outputs are adjusted to the local scale. Dynamical downscaling, on the other hand, feeds the global model outputs into a higher resolution regional climate model. Statistical downscaling usually requires less computational effort than dynamical downscaling, making it well-suited for analyses that need to show a range of future emissions to represent the uncertainty inherent in climate projections. Meanwhile, dynamical downscaling captures a richer set of outputs—such as wind speeds and humidity—though it is limited in showing outputs from the range of scenarios and models.[18] Statistical downscaling is more common, due to the significantly fewer computational and human resources required to complete it.

There are several data sources for downscaled data for the contiguous United States such as the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections (DCHP) website that houses downscaled data sets. See Section 4.1.1 for a more complete list of resources.

[17] NCAR UCAR, n.d.
[18] Hayhoe and Stoner, 2012.

Note that although downscaling is important for detailed, site-specific analyses, downscaling does introduce some additional uncertainty into the data sets. The differences between the downscaling techniques can cause more variation in the ultimate projections than the differences in the models or climate scenarios.

4.2.1.4. Uncertainty

There are several sources of uncertainty in climate projection information that could affect the precise temperature or precipitation levels experienced in the future, but the signal of the overall trend (in increasing or decreasing levels) can be clear. Uncertainty, therefore, is not a reason not to act on climate change. In fact, many data sets used in transportation planning and design have inherent uncertainty. Fortunately, there are ways to manage uncertainty, such as by looking at a range of scenarios.

Types of Uncertainty

Uncertainty in climate projections comes from three main sources. One is **scientific (or model) uncertainty**. This uncertainty is inherent to scientists understanding and ability to numerically capture climate processes. Although science and climate models continually improve, different climate models are likely to project different changes to the climate even when using the same GHG assumptions. Sometimes the differences between climate models are minor; sometimes they are significant (see box: Temperature vs. Precipitation Uncertainty for an example). To address this uncertainty, it is important to look at data from an array of models, rather than basing an analysis on any single model.

Scenario (or human) uncertainty, on the other hand, results from our inability to predict human behavior. Scenarios (e.g., RCPs; see Section 4.2.1.1) are built on varying assumptions about economic activity, energy sources, population growth and other socioeconomic factors, and lead to varying levels of GHG concentrations, which serve as inputs to climate models. The IPCC does not assign probabilities to the RCPs, so no scenario is officially considered more likely to happen than another (although some analysts believe that some scenarios are more realistic than others, as discussed in Section 4.2.1.1). Though it may be tempting to select a middle scenario rather than commit to one of the more/less extreme ones, there is no reason to assume that a middle scenario is more likely to actually occur than one of the others.[19] To address this uncertainty, it is advisable to look at multiple scenarios to understand the range of potential outcomes.

[19] Hayhoe and Stoner, 2012.

A third type of uncertainty relates to **natural variability in the climate system**, also known as natural uncertainty. Climate and weather have natural variations year to year, and any single year may not be representative of overall trends. This type of uncertainty should be dealt with by averaging climate projections over the course of two to three decades, rather than relying on a projection for a single year.[20] Time periods of the projections may thus be expressed in terms such as near-term, medium-term, and end-of-century (or similar terms), rather than a specific year. For example, a near-term timeframe might be 2010–2039, medium-term might be 2040–2069, and end-of-century might be 2070–2099. These increments often (but not always) represent an averaging of the values for each year within the increment. The averages provide insights into overall trends, without being unduly influenced by outlier years. Although climate projection data can be expressed for a specific year, it is not advisable to look at only a single year.

Temperature vs. Precipitation Uncertainty

The uncertainty associated with climate projections of temperature and precipitation differs qualitatively (see Figure 8). There is often relatively good agreement in temperature projections across climate models. Furthermore, projected changes in temperature tend to rise somewhat predictably over time with increasing greenhouse gas concentrations. In other words, scientific uncertainty is lower.

For precipitation, on the other hand, different models sometimes project very different changes for a particular location; the models will even sometimes disagree on whether precipitation will increase or decrease in that location. For this reason, it can be highly misleading to use the average across models. Rather, it may be better to consider the full range of projection values, with consideration given to whether extreme outliers should be eliminated. In the *Gulf Coast 2* project, FHWA used a methodology that looked at the 5 percent and 95 percent points along the full range of model and emissions scenario outputs, for example, in order to identify "Wetter" and "Drier" storylines. In this bracketing approach, it is important to consider a wide range of emissions scenarios and timeframes to ensure a clear understanding of the full breadth of how precipitation could change in the future.

The relative contributions of these three types of uncertainty vary over time and also differ for temperature and precipitation projections, as shown in Figure 8. For example, for longer-term projections of temperature, human uncertainty is the greatest source of uncertainty, while scientific uncertainty largest for longer-term precipitation projections. In the near-term, natural variability in precipitation is larger than scientific uncertainty.

[20] Hayhoe and Stoner, 2012.

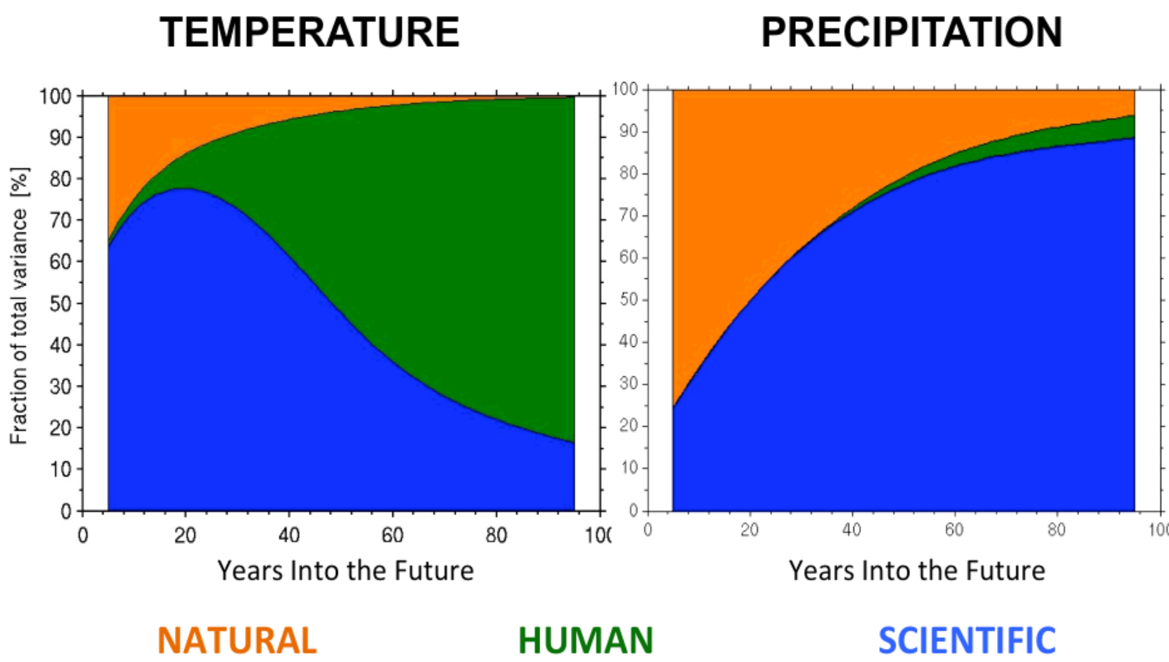

FIGURE 8: CONTRIBUTIONS TO UNCERTAINTY OVER TIME.

Source: Kotamarthi et al., 2016

Putting Climate Data Uncertainty into Context

It is important to put the uncertainty surrounding climate project data into context. Using climate change projection data may require some adjustments for transportation practitioners who are used to working with historical data, in that there is not one widely accepted data set, model, or set of assumptions. Practitioners may find the uncertainty surrounding the data unsettling, and be cautious about making decisions based on it.

However, it is important to remember that most data sets and models have underlying uncertainties and assumptions—it is not unique to climate change projections. For example, historical data sets are often incomplete and filled in using statistical assumptions. Meanwhile, major investment decisions are routinely made with support of traffic and other types of modeling—all of which contain assumptions about economic and population growth, demographic characteristics, traveler needs and preferences, land use patterns, etc. These assumptions may or may not hold true in reality.

Thus, although climate data uncertainty may appear in different ways than practitioners are familiar with, it will by no means be the first time practitioners make decisions based on uncertain information.

4.2.2. Developing Sea Level Rise and Storm Surge Projections

The subsections below summarize the key concepts to address when developing sea level rise and storm surge projections. Please see HEC-25 Vol 2 Section 2.3 for more detailed information about developing projections.

4.2.2.1. Sea Level Rise

An engineering analysis looking at sea level rise will ultimately need to determine the geographic extent of inundation from sea level rise, and, possibly, the depth of the water at a given point. This sort of exposure analysis is often done visually using GIS. However, to complete that exposure analysis, transportation practitioners must first estimate the amount of sea level rise that will take place, so that the inundation area can be spatially estimated. This section discusses how to estimate future sea level rise; it is assumed that this information is then used to estimate exposure of the assets being analyzed.

Sea level rise is generally discussed in terms of either global, eustatic sea level rise, or in terms of local, relative sea level rise. Eustatic sea level rise refers to the actual rise of the ocean, not accounting for subsidence of uplift of the adjacent land. Relative sea level rise considers the local uplift or subsidence of the coastal land, which can mitigate or exacerbate the local effects of eustatic sea level rise. For example, eustatic sea levels have been rising about 1.7 mm per year over the past century.[21] If, in a given location, the land is also subsiding 1 mm per year, the relative sea level rise is actually 2.7 mm per year. The Gulf and portions of the Atlantic Coasts in particular are experiencing land subsidence, meaning relative sea level rise might be more pronounced. Parts of Alaska and the Pacific Northwest are experiencing uplift, meaning relative sea level rise is less, or even negative.[22]

The expected rate of global sea level rise is somewhat controversial, with some evidence that the rate of rise has accelerated in recent years—the rate of global sea level rise since 1992, as measured by satellites, was about twice the rate observed over the 20th century[23]—but it is unclear whether that acceleration will continue. Thus, there is some disagreement within the scientific literature about how quickly sea levels will rise in the future. For example, the National Climate Assessment states that between 1 and 4 feet of sea level rise by 2100 is realistic, but also notes that for purpose of risk-based analyses, a larger range from 8 inches to 6.6 feet may also be appropriate. [24] The latest research from NOAA presents an even larger range, from 0.3 to 2.5 meters (1 to 8 feet), with a higher upper bound based on new models of ice melt processes.[25]

[21] IPCC 2013.
[22] FHWA, 2014.
[23] Walsh et al., 2014.
[24] Walsh et al., 2014.
[25] NOAA, 2017a.

Global sea level rise estimates need to be adjusted to account for local subsidence and uplift, and other geomorphologic processes. In addition, analyses must consider the effect of tides on water surface elevations to evaluate the full potential exposure under future conditions. Ultimately, all this information must be spatially applied or otherwise evaluated to determine the exposure of the transportation asset(s) under consideration. Please refer to HEC-25, Vol 2 Section 2.3.1.3 to see a detailed step-by-step example of how to estimate sea level rise. It should also be noted that the science of estimating sea level rise is evolving, and current methods do not account for future changes in regional water levels tied to variations in wind patterns, ocean circulation, etc.

4.2.2.2. Storm Surge

There is significant uncertainty regarding how climate change will affect the frequency and severity of coastal storms, with different models projecting different effects from climate change. However, the National Climate Assessment notes that, in aggregate, the models indicate an increase in the severity of storms, even if the frequency of total storms stays the same or even decreases slightly.[26] These storms will create storm surge, which can cause significant temporary flooding that can be extremely damaging to infrastructure. In addition, sea level rise can change the extent and depth of storm surge. Thus, transportation officials may wish to consider the exposure of their transportation system to more intense storms and associated surge.

Surge characteristics, including the effect of sea level rise on storm surge, are determined by complex coastal processes (see Section 5.2). Understanding the magnitude and characteristics of potential storm surges requires assumptions about plausible storms and sea levels, followed by using coastal models to characterize the storm surge and its associated waves. Storm surge and wave modeling is often more resource intensive than obtaining temperature or precipitation information. However, because of the potentially catastrophic consequences to coastal infrastructure, this type of modeling may be a worthwhile investment. In addition, pre-existing surge modeling is available for some locations, including results for the North Atlantic coast from the Army Corps' North Atlantic Coast Study, and the entire U.S. Atlantic and Gulf of Mexico coastlines from NOAA's SLOSH modeling.

Incorporating Sea Level Rise in Surge Modeling

FHWA recommends that practitioners consider using a range of both sea level rise and storm scenarios when modeling surges. For example, a low and a high sea level rise scenario could be coupled with a less intense and more intense storm event. Doing so will better represent the full range of plausible scenarios, and can also provide insight into whether sea level rise or storm characteristics are bigger drivers of the ultimate exposure.

[26] Walsh et al., 2014.

It is important to note that sea level rise is not necessarily a linear addition to storm surge; that is, a one-foot rise in sea level can result in more than one foot of surge for the same storm level. Sea level rise should be calculated first, and then the consequent impacts on surge can be estimated using a coastal storm surge model. Other models may also be used to characterize waves and other features. Example coastal models that can be used for storm surge analysis are shown in Table 4.

Wave Modeling

Although discussions of this coastal damage mechanism often center on "storm surge," it can be the waves or other processes that cause the most damage. Several case studies cited in the report found that waves, on top of the surge, caused the most damage to infrastructure. In fact, at least one case study found that higher surge levels that completely inundated an asset were overall less damaging than moderate surge levels that caused waves to repeated strike the asset (see Section 5.2). Thus, practitioners should usually include wave modeling, particularly for high-cost assets. Similarly, other models can capture erosion and other features that might be highly relevant for a given site.

Saffir-Simpson Hurricane Wind Scale: Not a Predictor of Surge

Hurricanes are commonly referred to by their designations under the Saffir-Simpson Hurricane Wind scale—e.g., a Category 4 hurricane. However, it is important to remember that this scale is based on wind speeds only, and is not an indicator of the surge associated with the storm. Surge is affected by storm track and the shape and depths of the coast. Thus, it would not be accurate to look at the surge associated with a given hurricane and assume that similar surges would occur elsewhere under the same category storm. It is also not an effective goal to attempt to engineer coastal infrastructure to withstand surges associated with a Category 4 or 5 hurricane—the goal would need to be articulated in terms of surge characteristics to be effective.

Please see HEC-25 Vol 2 for detailed guidance on how to develop storm surge projections.

TABLE 4: EXAMPLE NUMERICAL COASTAL MODELS[27]

Model/Program	Comments
ADCIRC	Hydrodynamic model (often used to model storm surge)
SLOSH	Storm surge model
ET-SURGE	Storm surge forecasting model
DELFT-3D	Hydrodynamics, waves, and morphology model
MIKE-21	Hydrodynamics, waves, and morphology model
FVCOM	Hydrodynamic model

[27] FHWA, 2014.

Model/Program	Comments
WAM	Wave model
STWAVE	Wave model
CMS	Hydrodynamics, waves, and morphology model
SWAN	Wave model
CH3D	Hydrodynamic model
EDUNE	Dune erosion model
SBEACH	Cross-shore morphology model
XBEACH	Hydrodynamics, waves, and morphology model
CSHORE	Cross-shore wave and morphology model
CHAMPS	Cross-shore wave and morphology model

4.3. Variables Commonly Used in Engineering Designs

The previous sections of this chapter have discussed climate projection information for the climate variables temperature, precipitation, sea level rise, and storm surge. While these variables are important to consider, transportation assets can also be significantly affected by secondary effects. For example, changes in precipitation patterns can lead to drought which can increase the risk of wildfire, which can eventually lead to greater risk of severe flooding due to consequent debris flows.

Furthermore, "temperature" and "precipitation" and similar terms are broad categories of climate variables. Climate models provide daily projections of temperature (high/low) and precipitation. Engineering designs often require very specific temperature and precipitation variables, such as the 2 percent annual return period (i.e., the 50-yr) rainfall depth, which can be calculated from the raw data that the climate models produce. Thus, some analysis may be needed to translate raw data into the appropriate variables that are relevant to the analysis at hand.

4.3.1. Relevant Climate Stressors

Prior to beginning an analysis, transportation practitioners should consider which stressors (e.g., temperature, precipitation, sea level rise) could affect an asset. One way to do this is to tap into existing agency knowledge. Agency staff are quite familiar with how the system and individual assets have been affected in the past by extreme weather conditions, such as flooding, heat waves, droughts, etc. Understanding how past weather events have affected the system or assets can provide a baseline for recognizing how future changes could affect roads and bridges.

For weather and climate conditions that currently do not pose concerns, practitioners should consider whether those climate stressors could cause problems if they became more severe in the future. Practitioners may wish to consult FHWA's Transportation Climate Change Sensitivity Matrix, which documents what is known in the scientific literature about transportation asset sensitivities to a range of climate stressors (see Table 5 below).

Some facilities might be affected by multiple or compounding climate stressors, so it is critical to consider not only whether a certain climate stressor could adversely affect an asset, but how it interacts with other stressors in combination. For example, warmer temperatures and longer breeding seasons could lead to more parasitic insects (such as the mountain pine beetle in western North America), which can further weaken trees already affected by drought (and thus unable to produce insect-repelling sap), producing more fuel for wildfires, which can exacerbate runoff and threaten culverts and roads. This situation has been extensively documented in western states for at least three decades.[28] Another example is that longer periods of more severe drought can lead to increased runoff when it does rain—resulting in more extreme flooding, thus illustrating that it can be important to consider changes in both drought and heavy precipitation.

TABLE 5: CLIMATE CHANGE STRESSORS THAT COULD AFFECT ASSET CATEGORIES, ACCORDING TO FHWA SENSITIVITY MATRIX[29]

	Climate Change Stressor							
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	✔	✔		✔	✔			

Note: In the table, check marks indicate where there is a documented relationship between the asset type and the climate change stressor, X's indicate where it is very unlikely that there is a relationship between the asset type and the stressor, and blanks indicate where there is little or no research on the topic.

Source: FHWA Sensitivity Matrix is available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/phase2_task2/sensitivity_matrix/

[28] Melillo et al., 2014.
[29] FHWA, 2012.

4.3.2. Common Variables used in Designs

Outputs from climate models generally require substantial post-processing to calculate temperature and precipitation variables relevant to transportation engineering and planning. For example, for purposes of selecting appropriate materials (such as asphalt binders), temperature data are used to calculate extreme variables such as the temperature of the hottest day of the year, maximum seven-day air temperature, the number of days above 95°F, the length of heatwaves, etc. for specific future time periods. Similarly, engineers may need information on soil moisture, flow rates, or other factors that can be calculated using the precipitation outputs from climate models, but the climate models themselves do not estimate these climate variables, thus necessitating the need for additional data processing.

When discussing the climate projection data, the specific design of an asset will help to select the appropriate climate variable format. For example, culverts might be affected by heavy precipitation, but it is actually the peak flow of the stream over a short time that causes the most damage. Research into an asset's design specifications would point out the need for information on peak flow[30] rather than on, for example, annual average rainfall. In general, extremes and shorter-term expressions (e.g., daily maxima) of climate projections are more relevant to engineering disciplines than longer-term averages (e.g., decadal average).

Projecting Climate vs. Weather

Temperature and precipitation projections can be expressed in many different ways, from estimates of daily temperatures to monthly, seasonal, and annual highs, lows, and averages. Uncertainty tends to increase when looking at shorter-term events (weather) and decrease when looking at longer-term ones (climate). Models may tend to show more similar values when looking at, for example, an annual or seasonal average, but may differ more when considering, for example, the temperature of the hottest day in August.

When looking at shorter-term events, therefore, it is especially important to consider a broader range of model outputs.

Appendix B: Table of Derived Climate Variables serves as a guide to possibly relevant climate variables, based on the variables used throughout the recent case studies. The last column of the table also indicates whether the variable is readily accessible in FHWA's CMIP Climate Data Processing Tool. If a particular variable is of interest and it is not included in the CMIP Climate Data Processing Tool, the specific methodology in the associated case study may be used to calculate it.

For additional information on resources, see the "Develop Climate Inputs" module of the FHWA Virtual Framework.[31]

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[30] Peak flow estimates would be an output from running a hydraulic model that uses climate model precipitation data as an input. Identifying the need for this sort of information upfront is therefore important to ensure resources are leveraged effectively.

[31] FHWA, 2016c.

5. Completing Engineering Assessments and Design

Once climate information has been obtained, transportation practitioners are ready to evaluate their transportation project's potential vulnerabilities to climate change, and then identify, evaluate, and select adaptation measures. Organized by engineering discipline, this chapter discusses how each discipline is potentially affected by changes in climate, the existing FHWA guidance available related to the discipline and climate change topics, and key lessons learned from the case studies about assessing climate change impacts on transportation. Then, the chapter summarizes the adaptation strategies explored in each case study, and notes remaining research gaps.

Practitioners should read the Overarching Lessons (Section 5.1), in addition to the sections related to their specific discipline. The Overarching Lessons section highlights findings that are applicable to two or more disciplines. For example, lessons about flooding may be applicable to both coastal and riverine environments.

In this early stage of climate change and transportation engineering study and analysis, sharing lessons learned and developing a community of practice is a proven way to expand a transportation agency's ability to address climate change and extreme weather risks. However, it is important for practitioners to remember that every asset and location is unique. The case studies reviewed for this chapter focused on specific assets in specific locations and each of the studies acknowledged and accounted for the local aspects of the assets. Practitioners should exercise care in applying the lessons learned directly to any other situations or in assuming that they represent appropriate conclusions for national policy guidance.

5.1. Overarching Lessons Learned

The case studies presented throughout this report offer many lessons that are broadly applicable across climate hazards and engineering disciplines. These overarching lessons fall into seven main categories:

1. Scoping Asset-Level Adaptation Assessments
2. Applying Climate Science and Managing Uncertainty
3. Integrating Climate and Weather Risks into Asset Management
4. Breaking Down Silos
5. Selecting and Implementing Adaptation Measures
6. Understanding Conservatism in Design Assumptions
7. Considering the Bigger Picture

The lessons are explained in more detail with supporting examples in Table 6 and the subsequent sections.

Table 6: Summary of Overarching Lessons Learned

Lesson Category	Lessons Learned
Scoping Asset-Level Adaptation Assessments	Flexible approaches are best.
	Focus data collection on the most critical elements, utilizing readily available data.
Applying Climate Science and Managing Uncertainty	While engineers should alter the inputs to engineering analyses due to climate change, the applicable design standards should not be altered.
	The use of historic climate data in lieu of climate projections is sometimes appropriate, but historic data should always be as up to date as possible.
	Maintenance records from extreme weather events can help practitioners understand the likelihood of future infrastructure damage.
	Historical climate data may be useful for a first-cut assessment of relative vulnerability and to narrow the number of assets that require detailed analysis, but to incorporate non-stationarity into a design, climate modeling projections should be used.
	Climate projections developed specifically for the study region by qualified climate scientists/modelers can help account for unique considerations.
	Existing tools can translate climate model outputs into variables that are appropriate for engineering design.
	Practitioners can compare climate projections to historical/observed climate values to increase integrity of results.
	The range of possible future emissions and climate scenarios should be considered, rather than focusing on just one projected scenario.
	Increases in the frequency of smaller, nuisance events should be considered in addition to extreme weather events.
	Given climate uncertainty, taking an incremental approach to adaptation may help reduce the risk of overspending while still increasing resilience.
	To avoid misinterpretation, engineers need to understand differences in conflicting future precipitation climate narratives that may be generated by groups of various climate models.
Integrating Climate and Weather Risks into Asset Management	Feeding information gathered and produced through engineering-informed adaptation studies into asset management programs may assist with more robust decision-making.
	Data generated from asset management systems may be leveraged to augment engineering-informed adaptation studies.
	Climate change and extreme weather event risks should be considered alongside other risks and agency priorities in asset management plans.

Lesson Category	Lessons Learned
	Practitioners may want to consider the impact of future environmental conditions on deterioration rates when conducting lifecycle planning.
Breaking Down Silos	Coordination among agencies with a vested interest in infrastructure resilience limits incompatible initiatives.
	Dialogue and communication across disciplines helps discourage barriers when undertaking climate change studies.
Selecting and Implementing Adaptation Measures	It may be helpful to define failure and how it could occur before selecting an adaptation strategy.
	Existing infrastructure designed using current or older climate data sets may still have a level of resiliency under future climate conditions.
	Many climate adaptation measures will be amplified forms of countermeasures currently installed to manage risks associated with today's environmental conditions.
	When selecting adaptation measures, the remaining life of the facility is important to consider.
	An adaptation portfolio approach to risk mitigation is likely to result in a suite of potentially viable options.
	When conducting analyses and selecting adaptation measures, policy-makers should provide guidance on risk tolerance across assets.
	Ecosystem-based adaptation and non-structural solutions may provide similar protection but broader project benefits.
	Long-term strategic land use planning can be an alternative to modifying the transportation asset.
Understanding Conservatism in Design Assumptions	Multiple conservative assumptions can compound to produce an overly conservative result.
	Additional criteria routinely applied in designs may provide additional conservatism.
Considering the Bigger Picture	Regional or corridor-scale vulnerability and criticality screens bring focus to asset-level studies.
	Sometimes the most appropriate adaptation measure can only be identified when considering the bigger picture.
	Avoid creating stranded assets or "adaptation islands."
	An adaptation strategy at a broader geographic scale may be appropriate.
	When evaluating adaptation strategies, it is important to consider potential secondary impacts or cascading consequences of a failed asset.
	Potential impacts on adjacent property due to proposed construction conditions should be addressed when designing for adaptation in urbanized areas.

Lesson Category	Lessons Learned
	Post-event assessments of damage mechanisms can provide information for enhancing resilience to extreme events.
	Marine vessels have lower adaptive capacity than road users to disruptions at coastal bridges.

5.1.1. Scoping Asset-Level Adaptation Assessments

Conducting robust asset-level studies of climate change impacts and adaptation options is a relatively new area of study. This section summarizes lessons learned from scoping asset-level engineering-informed climate adaptation assessments.

Flexible approaches are best. There is no one-size-fits-all approach to conducting engineering-informed adaptation assessment processes. It is important for practitioners to keep their end goals, timeframes, and budgets in mind, rather than try to adhere to a process too strictly. For example, through trial and error the *TEACR Slope Stability*[32] study found that an economical first step in analyzing a slope suspected of being at risk of failure due to increased precipitation is to conduct a simple preliminary investigation to provide insights on the vulnerability of the slope. If the preliminary analysis indicates the possibility of failure, then a detailed analysis is needed (see Section 5.4 for more information on pavement and soils studies). By conducting a simpler and streamlined screening analysis, practitioners could save considerable time and expense in instrumentation and data collection.

Focus data collection on the most critical elements, utilizing readily available data. Before embarking on a data collection effort, consider the questions to be addressed and what level of detail is needed, given the available resources and timeframe. If the ideal data are not available, prioritize the most critical data for collection, and use proxies for deficient data. Where possible, leverage asset management and maintenance management system information. This approach is exemplified in the *MassDOT Pilot;* MassDOT used their asset management data and supplemented it with field visits to critical assets and interviews with maintenance staff to gather institutional knowledge.

5.1.2. Applying Climate Science and Managing Uncertainty

Applying climate science to transportation analyses and managing uncertainty about a changing climate are relatively new practices compared to traditional engineering practices. This section summarizes lessons learned from applying climate science to transportation decision-making.

While engineers should alter the inputs to engineering analyses due to climate change, the applicable design standards should not be altered. FHWA, AASHTO, and state DOTs have

[32] Throughout this section, case studies are referred to by an abbreviated title. For a full list of the case studies referenced in this report and their complete titles (with hyperlinks), see Appendix A: List of Case Studies.

developed design standards for riverine crossings based on an allowable level of hydrologic risk for different types of structures and conditions. Applicable design standards could include allowing 1 foot of freeboard between the 25-year flood and the bottom of a bridge or designing an interstate to not overtop at the 100-year storm event. When considering potential future conditions, the risk component of these types of infrastructure should not be thought of as shifting; rather the engineer should consider how the design input necessary to meet the standard is shifting with climate change.

An example would be a bridge design standard that calls for an assessment of the 1 percent annual exceedance probability streamflow. The current 1 percent annual exceedance probability is associated with a streamflow of 10,000 cubic feet per second (cfs). Due to shifting climate conditions, extreme event precipitation changes such that the flows reflect 10 percent higher values than before, thus the 1 percent flood event shifts to 11,000 cfs. In this case, the design standard for assessment of 1 percent flood event remains the same, while the input variable of the 1 percent flood flow rate is the shifting variable.

The use of historic climate data in lieu of climate projections is sometimes appropriate, but historic data should always be as up to date as possible. The use of updated historical climate data (e.g., NOAA Atlas 14[33] precipitation frequency estimates, which replaced older data sets such as the TP 40[34] data from 1961) are appropriate for decisions on the near-term horizon, for low-criticality assets, and as the basis for comparing to projections of future changes in climate. However, practitioners should be wary of using outdated data that does not capture recent trends in climate. For example, the primary lesson learned from *TEACR Pavement Freeze-Thaw* is that some standard metrics used by engineers, such as the “State of Maine Design Freezing Index,” have been prepared with data that are now out of date.

Maintenance records from extreme weather events can help practitioners understand the likelihood of future infrastructure damage. In *ODOT Pilot* ODOT used maintenance dispatch records to determine storm event thresholds that trigger road hazards. ODOT then used future climate projections to determine how frequently the storm event thresholds would be exceeded in the future. Tying future impacts to past damages can help make the study findings more understandable.

Historical climate data may be useful for a first-cut assessment of relative vulnerability and to narrow the number of assets that require detailed analysis, but to incorporate non-stationarity into a design, climate modeling projections should be used. The advantages of using historic data are the readily available nature of the data sets, the ability to utilize all existing engineering tools in the analysis, and the ability to quantify current levels of uncertainty in the data set. The *CT DOT Pilot* study provides an example of how a research team

[33] NOAA Atlas 14 point precipitation frequency estimates are available at: http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html.
[34] Hershfield, 1961.

can draw conclusions about system resiliency using historical data. The *CT DOT Pilot* study quantified excess capacity of culvert and bridge structures under historical conditions to draw conclusions about future resiliency. Greater excess capacity in the existing structure could indicate greater resilience, though this does not account for other localized factors such as land use change, difference in slopes, and time of concentration.

The downside of this approach is that it does not explicitly quantify non-stationarity at a study site, which could vary from site to site in a region even if the precipitation changes are uniform. In this case, while the traditional historical analysis method can identify the amount of excess capacity in a piece of infrastructure, it does not inform the research team on whether or not that amount of capacity is sufficient for future changes over the life of the asset. When looking at large amounts of infrastructure, as was done in the *CT DOT Pilot* study, it may be useful or necessary to use this approach to develop an initial prioritized list of assets that will need to be addressed in the future. Further detailed study, using climate model projections, can then be undertaken to more accurately account for non-stationarity trends in precipitation patterns and to provide more robust information to help a designer choose a replacement structure or adaptation option.

Climate projections developed specifically for the study region by qualified climate scientists/modelers can help account for unique considerations. Climate projections developed for a wide geography are useful for understanding general trends, but they may introduce uncertainties when applied to a smaller study area or a different timescale. While readily available climate projections (e.g., from the US DOT CMIP Climate Data Processing Tool) are likely sufficient for most studies, highly detailed studies of complex, critical, and long-life assets, or studies with unique considerations may require the development of unique climate projections.

Chapter 7 of HEC-17 suggests a tiered level-of-effort approach to incorporating climate change and non-stationarity into hydrologic design of drainage infrastructure. It recommends hiring a climate scientist and using projected climate model discharges for complex, critical, long-life assets. For instance, the *IDOT Pilot* project's climate scientist was able to select appropriate downscaled climate model information and provide the expert hydrologists working on the project with the necessary precipitation values for their highly detailed watershed model. These experts were familiar with the types, durations, and seasons of storm events that produced the highest runoff values. The IDOT study team decided they need only collect daily precipitation data during the traditional flooding season of late spring to early summer. This saved time and money by reducing the amount of data needed for analysis. Additionally, the expertise of the universities in climate modeling ensured that the data were appropriately developed and that uncertainties were appropriately accounted for.

Existing tools can translate climate model outputs into variables that are appropriate for engineering design. Climate projection data, which outputs daily variables for temperature and precipitation, can be used to calculate many (but not all) values used for designing infrastructure. For example, daily temperature projections can be converted to variables such as annual minimum or maximum temperature, average daily minimum or maximum temperature, seasonal averages, consecutive days above a temperature threshold, three-day average maximum temperature, etc. Existing resources such as the US DOT CMIP Climate Data Processing Tool can easily provide these secondary variables at a refined geographic scale. For more information on resources and tools, see the Chapter 4.

Practitioners can compare climate projections to historical/observed climate values to increase integrity of results. Comparative analyses improve familiarity and credibility of climate model results and highlight areas where alternate designs may be needed. For instance, comparison of the statistical confidence limits (e.g., comparison to 95 percent confidence limits) can help engineers understand the uncertainty associated with climate data. For example, in the *IDOT Pilot* study, the research team placed confidence intervals on engineering metrics computed from climate projections, which allowed IDOT's bridge engineers to consider different flood quantile discharges as a possibility for design criteria.

The range of possible future emissions and climate scenarios should be considered, rather than focusing on just one projected scenario. Practitioners cannot assume that increases in greenhouse gas emissions will automatically result in increases in extreme weather events. Below are a few considerations for selecting a range of scenarios:

- When developing temperature projections past mid-century, the selection of greenhouse gas emissions scenarios, rather than climate models, will have a greater influence on the projected changes. This is because the farther out practitioners look, the wider the range of uncertainty in future greenhouse gas emissions production.
- When developing precipitation projections, the model selection and uncertainty can have a particularly strong influence on projections, irrespective of the emissions scenario chosen. Additionally, while most climate projection data sets indicate an increase in springtime rainfall in most locations, the increase is not necessarily larger under higher greenhouse gas emissions scenarios. For example, in the *TEACR Culvert* study, FHWA found that averaging across the climate model precipitation projections created significant dampening of potential change, particularly as some models might suggest a reduction in magnitude while others might suggest an increase. To deal with this issue and to consider climate model/scenario combinations (i.e., simulations) that span across the range of projections, FHWA isolated and evaluated both the most extreme and the least extreme precipitation simulations.

Increases in the frequency of smaller, nuisance events should be considered in addition to extreme weather events. Practitioners often focus on the changes in frequency and intensity of extreme events, but climate change may change the frequency of smaller events that also contribute to repeated stress and ultimate failure. Increased frequency of smaller rainfall events, for instance, can increase soil moisture over time and affect pavement reliability. The

TEACR Pavement Shrink-Swell study discusses the effects of load repetition on pavement with weakened subgrades due to relatively small changes in temperature and precipitation.

Given climate uncertainty, in some cases taking an incremental approach to adaptation may help reduce the risk of overspending. The uncertainty of future impacts combined with the potential high cost of worst-case scenario adaptation strategies dictate that an incremental approach to implementing solutions is warranted. Where possible, practitioners should identify "no regrets" adaptation options that provide value under a range of potential futures, and can be readily adjusted or augmented pending changes in environmental conditions. This is facilitated by the relatively slow rate of climate change. For example, in the *Sandy: Governor's Island Ventilation Building* study, the New York Metropolitan Transportation Authority recommended designing an improved flood wall around the study asset, a ventilation building, in a manner such that it could be enhanced (e.g., additional height, additional strength) if warranted in the future (see Figure 9). Monitoring of future changes in flooding would inform the need for and timing of enhancement of the adaptation option.

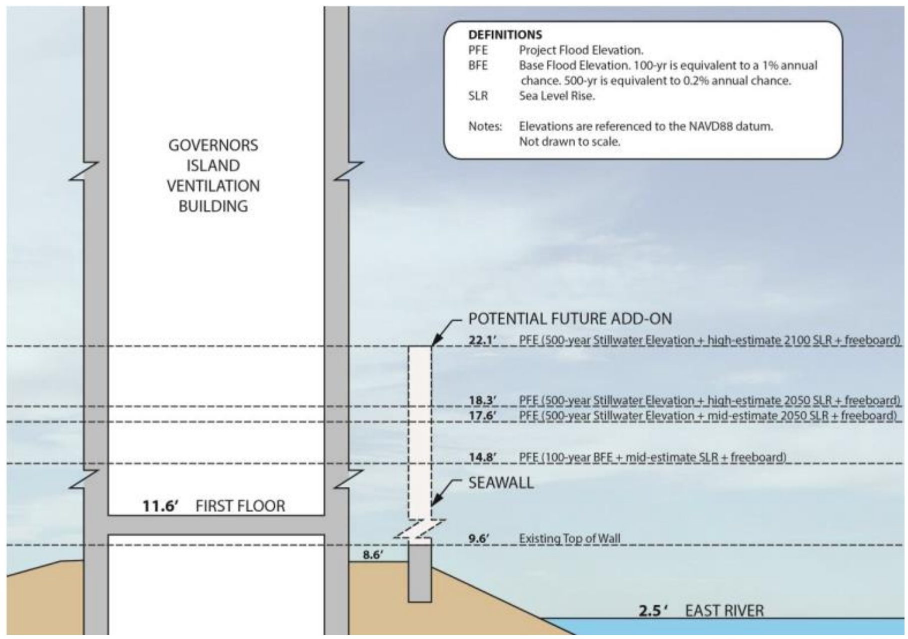

FIGURE 9: PROJECT FLOOD ELEVATION DIAGRAM.

Source: *Sandy: Governor's Island Ventilation Building*.

As another example, in the *TEACR Slope Stability* study, the study team reviewed how Virginia Department of Transportation (VDOT) has used an adaptive management strategy to manage climate uncertainty and the inherent uncertainty of un-seen soil conditions and landslides. VDOT began by monitoring slope movement, installed a "toe wall" anchored by soil nails to stabilize the slope, and developed a plan for additional measures that could be taken if the slide continued to progress. In adaptive management, each measure should not preclude the installation of subsequent measures or reduce their effectiveness.

To avoid misinterpretation, engineers need to understand differences in conflicting future precipitation climate narratives that may be generated by groups of various climate models. The *TEACR Culvert* study demonstrated a case where statistical analysis of precipitation climate data misrepresented the future climate conditions that were being projected by the climate models. In the study, competing climate scenarios were telling two distinct narratives—some models were predicting significant decreases in extreme event precipitation, while others were predicting significant increases. When the FHWA study team compiled the ensemble statistics little to no changes were predicted (due to the averaging out of the increases and decreases). In this case, it was important for the study team to realize that the statistics were not properly representing the precipitation narratives being conveyed by the climate models. To account for this, specific climate model runs were used to understand what a “wetter” future and a “drier” future would mean for the culvert.

5.1.3. Integrating Climate and Weather Risks into Asset Management

Asset management helps DOTs strategically and systematically sequence maintenance, preservation, repair, rehabilitation, and replacement actions. Good asset management systems help decision-makers allocate limited resources across these actions to maximize overall system performance. Integration of climate change and extreme weather into asset management systems bolsters existing decision-making processes by incorporating climate risk considerations. This section describes lessons learned from the case studies related to asset management and climate and weather risks.

Feeding information gathered and produced through engineering-informed adaptation studies into asset management programs may assist with more robust decision-making. Information from engineering-informed adaptation studies can inform asset management programs under a changing climate. For instance, in the *NYSDOT Pilot*, *CT DOT Pilot*, and *MnDOT Pilot*, the research teams collected and produced targeted data that can benefit future engineering-informed adaptation studies and can assist asset managers in making asset management decisions. The data included accident data, damage data by site rather than event, ratings of pavement and culvert conditions, and data on willingness to pay for upgrades in culvert replacement projects (gathered via public surveys).

In the *MnDOT Pilot* study, the research team customized a system-wide hydraulic model-screening tool to inform their vulnerability analysis, and to interface with their asset management database. As next steps, MnDOT is considering incorporating vulnerability assessment scores into their asset management databases and their asset management plan, and gathering additional data to include in their asset management system that would be useful to future flood vulnerability assessments.

Data generated from asset management systems may be leveraged to augment engineering-informed adaptation studies. Strong asset management systems (e.g., bridge and pavement management systems) can provide the data needed to conduct engineering-informed adaptation studies. Lack of accessible and compatible asset data for climate change assessments was among the most frequent issues encountered by the FHWA Climate Resilience pilots. Asset management systems can serve as a repository of information, such as asset condition and extreme weather damage data, in a consistent format that is already compatible with the agency’s existing systems. Increasing the use and quality of asset management data systems would help agencies have access to the data they need to complete climate change assessments.

Climate change and extreme weather event risks should be considered alongside other risks and agency priorities in asset management plans. Asset management provides an approach to consider climate change adaptation in the face of multiple decision-making objectives. For example, asset management can be used to coordinate culvert replacements to adapt to changing stream flow and flooding conditions with regularly scheduled pavement rehabilitation projects. Asset management decisions should not be made solely on climate change risks, but these risks should be considered alongside the other risks currently addressed by asset management decision-making processes.

Practitioners may want to consider the impact of future environmental conditions on deterioration rates when conducting lifecycle planning. For instance, factoring future projected temperature conditions into deterioration of pavement calculations, and sea level rise and storm surge projections into damage to coastal road estimates may be productive. The timeframe of projected change should match the design life of the piece of infrastructure (e.g., pavements designed for 20 years should consider climate projections of about 20 years instead of to 2100).

In the *NCTCOG Pilot*, NCTCOG considered conducting an analysis of how extreme weather events affected pavement deterioration since the City of Dallas has a robust data set of historical street conditions, including the extent and severity of pavement distress. However, since the database is not currently configured to correlate extreme weather effects to specific street section degradation or failures, NCTCOG is recommending that the city improve its monitoring of weather-related stresses as part of its pavement management system.

5.1.4. Breaking Down Silos

Addressing climate change risks requires an interdisciplinary approach. To effectively evaluate and adapt facilities, it is vital that agencies, departments, and staff coordinate and contribute their respective expertise. This section provides a synopsis of lessons learned from the case studies on dismantling barriers between agencies, departments, and staff.

Coordination among agencies with a vested interest in infrastructure resilience limits incompatible initiatives. Collaboration and coordination with other agencies such as the U.S. Army Corps of Engineers (the Corps) and Federal Emergency Management Agency (FEMA), which are conducting work related to infrastructure resilience may strengthen analyses, limits duplication of efforts, and improves consistency across projects. For example, in the *WSDOT Pilot*, the research team worked with the Corps and the local public works department to leverage research and findings from a recent major flood risk reduction study conducted in the area. WSDOT was able to rely on the Corps' research, which provided detailed information on existing conditions, including hydraulic data. WSDOT used the hydraulic data to determine the modeled maximum depth of highway flooding and the length of state highway flooded under various return interval storms. Ultimately, WSDOT found that collaboration with the flood risk managers in the study area was critical as it develops adaptation strategies. During adaptation strategy development, the study team uncovered locations where WSDOT could have invested in the wrong place if the team had been unaware of the Corps' plans. WSDOT flood adaptation strategies could have affected assumptions in the Corps' study by inadvertently blocking the flow of water that the Corps assumed would occur.

Dialog and communication across disciplines helps discourage barriers when undertaking climate change studies. Some of the most relevant groups to engage include engineers, maintenance staff, environmental staff, and science agencies. Maintenance staff can readily identify vulnerable areas or assets based on "on-the-ground" experience with recent extreme weather impacts and can help focus the scope of assessments. Environmental staff may help navigate potential obstacles such as environmental permit requirements for adaptation options. Some additional specific considerations for breaking down silos between disciplines include:

- **Engage climate science experts.** Coordination with federal, state, and local agencies working in climate science is critical to applying the "best available" scientific data and methods to climate change analyses. At the federal level, the USGS, National Weather Service, and the Corps are leaders in climate and hydrologic science. Enhancing communication among climate scientists, hydrologists, and engineers is key. The *IDOT Pilot* study exemplifies this coordination, multidisciplinary analysis, and collaboration, including engagement of climate scientists and hydrologists from local universities.
- **Interview DOT staff from a wide range of disciplines to develop a more robust understanding of vulnerability.** For example, FEMA's Special Flood Hazard Areas (SFHAs) do not necessarily match what has historically happened in flooding events due to varying performances of flood protection assets. As detailed in the *WSDOT Pilot* study, WSDOT conducted interviews with maintenance staff on impacts from recent flooding events to supplement the information from the SFHAs. In the final flood analysis, WSDOT combined information from historical data, workshops, and interview data with the SFHA assessments.
- **Include qualified engineers in all relevant disciplines, such as coastal modeling and local geomorphology analysis.** Local nuances are important, as is an engineering expert's understanding of the limitations and benefits of various model options. For example, selection of appropriate storm surge and wave computer models should be undertaken by experienced coastal engineers who know how to quantify risk from storm surge, know the physical processes and damage mechanisms to look at, and understand which models will give the most accurate results. A key aspect of the *TEACR Roadway Surge* study is that the team included coastal engineers for the planning and design of transportation facilities exposed to the unique wave, tide, and sand transport environment along the coast.

5.1.5. Selecting and Implementing Adaptation Measures

This section describes lessons learned from case studies focused on the selection and implementation of adaptation measures. Other chapters of this report provide additional observations on this topic that are pertinent to a specific stage of analysis and/or engineering discipline.

It may be helpful to define failure and how it could occur before selecting an adaptation strategy. In some places, a loss of service could qualify as failure while in other locations, the definition of failure may be the complete destruction of an asset. The agency's definition of failure for the asset in question can influence the selection of appropriate adaptation measures. For example, in *GC2 Bridge-Storm Surge*, FHWA evaluated various adaptation options for dealing with two failure modes to the bridge: superstructure failure from potential deck uplift due to storm surge, and substructure failure due to excessive lateral forces on the bridge piles. The different failure modes required different analysis approaches. Ultimately, the research team determined that the bridge is not likely vulnerable to uplift, but could be vulnerable to substructure failure.

Existing infrastructure designed using current or older climate data sets may still have a level of resiliency under future climate conditions. In cases where the remaining lifetime of the asset is short or the avoided costs of climate impacts (i.e., the benefits of adaptation measures) are low, it may be economically advantageous to consider the extent to which current measures (e.g., freeboard requirements) may be sufficient. The *CT DOT Pilot* research team focused its study on the performance of the existing culvert infrastructure, the condition of the culverts, and the resiliency of the current system. The research team noted that the culverts that meet current design standards can function during flood events that exceed their design frequency, as the design standard may include allowances for freeboard or overtopping that would not necessarily result in a failure of the roadway if exceeded. Age and physical deterioration may be more likely to contribute to failure rather than flow increases.

Many climate adaptation measures will be amplified forms of countermeasures currently installed to manage risks associated with today's environmental conditions. For example, in the *TEACR Roadway Surge* study, FHWA concluded that the existing countermeasure, a sheet pile wall and gabions, is a sound adaptation option for managing current weir-flow risks and future sea level rise and storm surge climate impacts.

When selecting adaptation measures, the remaining life of the facility is important to consider. Practitioners managing assets that are scheduled to undergo rehabilitation or full replacement in the near-term can delay implementing adaptation strategies until the anticipated rehabilitation and replacement cycle. Expected asset lifetime, relative to anticipated changes in climate, can influence the cost-effectiveness of adaptation options. For example, in *GC2 Pavement*, FHWA determined that changes to pavement mix designs to adapt to projected increases in temperature could be implemented during routine rehabilitation.

In another example, when the remaining design life of a bridge is short enough that expected sea level rise would not affect it during its design life, such as in *GC2 Navigable Bridge*, the bridge should not be raised until its eventual full replacement. This approach will be a more cost-effective solution than unnecessarily retrofitting the existing structure now. Likewise, in *Sandy: Loop Parkway Bridge*, NYSDOT decided to implement adaptation strategies at a bridge coincident with a planned mid-century rehabilitation. While the potential for climate-related impacts will remain in the interim, the cost savings of waiting to implement the adaptation measure outweighed the benefits of acting earlier. It can also be helpful for an agency to have updated designs or plans (that is, those designed to withstand future climate conditions) for critical assets "on the shelf" and ready to use if needed.

An adaptation portfolio approach to risk mitigation is likely to result in a suite of potential viable options. A single adaptation strategy may not fully mitigate climate risks, or a series of measures may be more effective and/or cost-effective, so it is beneficial to consider a combination of complementary adaptation measures to reduce risk. For example, in *GC2 Bridge Approach-Storm Surge*, FHWA identified that multiple existing protections, including bulkhead, riprap, and willow mattress, are all required to armor the abutment against scour. Additionally, a portfolio may include a combination of engineering and non-structural (e.g., ecosystem-based, operational) adaptation measures.

When conducting analyses and selecting adaptation measures, policy-makers should provide guidance on risk tolerance across assets. Within an agency, risk tolerance is likely to vary between asset classes, climate change stressors, or based on asset criticality. If an agency has a low risk tolerance for a particular asset then the agency may not be willing to tolerate multiple failure/recovery cycles, and therefore may opt for early replacement with a robust set of adaptation measures. An asset for which the agency has a higher risk tolerance may only require moderate risk mitigation investments or may even continue with just standard operation and maintenance activities. For example, NYSDOT has established a low risk tolerance threshold for sea level rise and storm surge. In line with its risk tolerance, NYSDOT used the high (90^{th} percentile) sea level rise projections for the *Sandy: Loop Parkway Bridge* study.

Ecosystem-based adaptation and non-structural solutions may provide similar protection but broader project benefits. The benefits of ecosystem-based solutions can be overlooked, especially when the environmental benefits are difficult to quantify in the economic analysis. In the *TEACR Living Shoreline* study, FHWA specifically evaluated the use of a living shoreline to determine its physical ability to protect a roadway from sea level rise and storm surge. Not only would a living shoreline provide ecological benefits, FHWA found that the living shoreline approach could provide protection for the roadway for decades before more costly structural adaptation measures would be required.

The *TEACR Culvert* study includes a discussion on ecosystem-based post-fire mitigation measures that can be used to slow flow rates and decrease debris flows in a watershed that has been recently burned. Examples of treatment includes hydro mulching, seeding, tree plantings, debris basins, and upland erosion control.

Long-term strategic land use planning can be an alternative to modifying the transportation asset. For impacts that may occur farther in the future, changes in land use can offer other potential adaptation measures that might not be identified during a transportation asset-level assessment. For example, in the *GC2 Navigable Bridge* study*,* FHWA notes that vertical clearance on the waterway might be compromised for large ships in the long term given sea level rise. Rather than adapting the study asset, it is feasible that the facilities past the bridge could be relocated to the other side of the bridge; or, smaller ships could be used instead. It is also possible that the facilities currently dependent on large ships will not be located in the study area by the time that sea levels rise enough for this to be an issue, and thus no adaptation will be necessary.

5.1.6. Understanding Conservatism in Design Assumptions

There are many ways to build in margins of safety when designing infrastructure. For example, when there is ambiguity about climate information, an engineer might choose to design to the more extreme scenarios. Assumptions regarding future climate scenarios, climate models, and timeframes are other opportunities to introduce conservatism. This section summarizes lessons learned about engineering conservatism as it relates to climate change analyses.

Multiple conservative assumptions can compound to produce an overly conservative result. Engineers use conservative assumptions in design development to account for the inherent uncertainty of design inputs or conditions. However, the compounding effect of multiple conservative assumptions can produce a result where the degree of over-design exceeds the intent of the engineering design team. Over conservatism is a point of concern for climate adaptation studies since climate change data adds multiple points of uncertainty, which may lead to engineers selecting multiple conservative assumptions without considering the compounding effects. Understanding and avoiding compounding conservative decisions during project design will help to avoid unnecessary over spending on infrastructure. Section 8.4 of HEC-17 recommends that practitioners establish the appropriate level of conservatism considering the end result of the process rather than at each stage of the design process. This approach requires communication between disciplines to ensure that hydraulics, geotech, structures, etc. understand the conservatism appropriate for the project.

An example of compounding conservative assumptions could be developing a conservatively high calibration to an existing conditions hydrologic model and then manipulating that model to project future conditions streamflow using 90^{th}-percentile climate change precipitation data. The combination would seemingly result in over-prediction of future streamflow due to the compounding conservatism.

Added conservatism can potentially affect benefit-cost decision-making analyses, as proposed in several of the case studies, due to interpretations of design standards and failure conditions.

Chapter 6.3 of HEC-17 includes a detailed discussion of the correlation between risk, design standards, and failure. It is important for research teams to recognize that exceedance of design standards does not necessarily equate with failure and that assumption as such may lead to overly conservative choices.

Additional criteria routinely applied in designs may provide additional conservatism. Typical criteria for designing transportation assets are based on a design event, such as a flood exceedance probability. Strict adherence to these criteria under a changing climate may lead to unjustifiable costs, especially in the case of low-criticality or short-lived assets. It is possible that exceedance of design criteria might occur during the design life. As discussed in Section 6.3 of HEC-17, although these exceedances may be considered a "failure," it is not always the case that negative consequences, in terms of public safety, asset damage or service interruption, will occur. In the *CT DOT Pilot* study, CT DOT evaluated bridge and culvert structures for hydraulic adequacy based on the current design criteria. Some design criteria include unquantified elements that contribute to the margin of safety in a design. These include headwater-to-depth ratios, limitations on backwater upstream of culverts, and 100- and 500-year check floods. These additional criteria may provide enough "cushion" to compensate for additional flow produced by climate change, although the change in climate would bring an increase in risk if it eats into the cushion.

On the other hand, transportation agencies in countries such as Norway and the Netherlands tend to use more conservative assumptions than their U.S. counterparts when developing climate science projections and calculating future flows. Both countries are early adopters of national or sector based strategies to address climate change impacts. In the case of the Netherlands, disasters caused by flooding may explain part of why they are willing to consider more extreme climate risk scenarios. Areas of the United States with concentrations of critical assets and people may also want to consider a similar strategy.

5.1.7. Considering the Bigger Picture

Facility-level analyses and proposed adaptation solutions should be appropriate within the broader context, such as regional adaptation, potential secondary impacts, surrounding land uses, and public feedback. This section provides an overview of lessons to apply when determining the scope and framing of climate-informed engineering analyses and the selection of adaptation measures. Economic considerations of adaptation solutions are a key factor in selecting a robust adaptation strategy and are described in detail in economic assessments. Additionally, specific considerations that go beyond engineering- and cost-effectiveness when selecting adaptation measures are described in Chapter 7.

Regional or corridor-scale vulnerability and criticality screens bring focus to asset-level studies. Before launching an asset-level adaptation study, a regional or corridor-scale vulnerability and criticality screen can help determine which locations or assets may warrant additional study. For example, the *MTC Pilot* first conducted a qualitative regional vulnerability assessment before selecting three critical and vulnerable geographic areas to invest in more detailed hydraulic analysis and the development of climate adaptation options.

Sometimes the most appropriate adaptation measure can only be identified when considering the bigger picture. For example, in the *GC2 Bridge Approach-Storm Surge* study, FHWA found that formulas for estimating scour are very conservative, leading agencies to protect foundations rather than design the foundations to resist scour. The analysis determined that features around the asset that protect the foundations like riprap and willow mats play an important role in the ability of an asset to withstand surge, and it is vital that inspectors look at the whole picture when inspecting assets.

In the *TEACR Economic Assessments,* one option that FHWA evaluated was replacing a box culvert that includes a flapper gate on the downstream side with a bridge. However, the flapper gate prevents saltwater from progressing upstream, and if replaced by a bridge, saltwater and tidal influence would be reintroduced into the estuary. As another example, in the *MnDOT Pilot,* MnDOT built upstream considerations into the design of their adaptation options by including stream restoration and floodplain enhancement for the specific purpose of backwater reduction. This strategy would also provide benefits for water quality improvement due to stabilization of erosion areas and depositional opportunities for suspended solids and nutrients.

In the *TEACR Coastal Bridge* study, the primary, historical damage mechanism was separation of the bridge decks from the substructure. The assumed retrofit adaptation measure to avoid this problem was to strengthen the connections between the deck and substructure. However, after analyzing the situation under increases in sea level rise, FHWA found that this adaptation measure alone would likely end in the destruction of the bridge due to other failure mechanisms slightly later in the storm. A key finding was that the only adaptation measure that will protect the bridge is to increase its elevation, perhaps in combination with some of the other structural modification adaptation measures considered.

Avoid creating stranded assets or "adaptation islands." Before developing adaptation strategies to address overtopping of bridge approaches, roads, and deck, debris overflow, and structural damage, practitioners should consider if the impacts to the area would be widespread. If most of the surrounding roads and community assets are projected to be impacted by flooding, then a regional approach to adaptation (such as retreating from the region, or holistic adaptation that goes beyond just transportation) may be more appropriate. For example, adapting a bridge makes little sense if it leads to an island that will be abandoned due to sea level rise. Meanwhile, adapting a single culvert may not be helpful if upstream/downstream impacts are ignored, or if nearby culverts are not similarly adapted.

An adaptation strategy at a broader geographic scale may be appropriate. It is worthwhile to look beyond the individual asset to determine if and how the surrounding area/infrastructure is also at risk to the same stressor. For example, in addition to adaptation strategies at the asset-level, *MassDOT Pilot* identified regional adaptation strategies. The regional strategies identified flood pathways from an adjacent section of the coastline that, if blocked, could protect large inland areas. MassDOT determined that regional solutions along the coastline can be more cost-effective compared to addressing individual assets, but often require coordination between and investment by multiple stakeholders.

Additionally, the *GC2 Culvert* study team noted that regional approaches to adaptation designs will provide for improved resiliency of the transportation network as a whole by mitigating weak links in the system (in the case of treating an entire roadway segment). It is equally important to consider the condition of downstream infrastructure to avoid passing increased hazard conditions onto undersized assets. For example, an undersized culvert in an upper stream reach may have served to attenuate peak extreme event flows downstream, so that upsizing that culvert will negate the attenuation and increase flows at a downstream bridge that may not be adequately prepared for the increase.

When evaluating adaptation strategies, it is important to consider potential secondary impacts or cascading consequences of a failed asset. For example, in *Sandy: Bergen Avenue, NY*, the study area's roadway provides the only access to the nearby wastewater treatment plant. During a storm event, if the plant does not have access to electricity, it is only able to operate for up to 24 hours using back-up generators, reserve fuel, and other supplies stored on site. Once these reserves are exhausted, the plant would have to shut down if they cannot be replenished by vehicles on the access road. When evaluating adaptation options, it is important to consider the broader consequences of roadway closure such as the potential inability to refuel the plant, which could result in untreated waste flowing into streets, homes, and bodies of water.

Potential impacts on adjacent property due to proposed construction conditions should be addressed when designing for adaptation in urbanized areas. For example, MnDOT design criteria state that the allowable headwater must be non-damaging to upstream property. Any changes in the flooding patterns of adjacent properties attributable to the design option chosen should be monitored. Similarly, in *GC2 Highway Surge*, widening a bridge opening was considered as an adaptation option, but it could potentially increase flooding downstream, cause construction disturbances, and increases costs. The potential for flooding would be increased because the larger opening under the bridge would expose more properties to potential storm surge. If this measure were to be seriously considered, public meetings could be held to explain the impacts and convey the facts to the public. Coordination with individual property owners would also be necessary if the adaptation strategy is expected to impact specific properties.

Post-event assessments of damage mechanisms can provide information for enhancing resilience to extreme events. Information from post-event assessments may indicate impacts and vulnerabilities that were not previously identified, and help evaluate the effectiveness of adaptation measures. For example, in the *TEACR Roadway Surge* study, FHWA used post-storm damage inspections to inform adaptation design decisions and specific design details. However, post-event forensic analysis is often hampered by the immediate focus on restoring service as quickly as possible. Practitioners may consider updating the post-storm damage inspection process to include inspection for specific items related to climate and damage mechanisms. This process to gather information on damages in order to enhance resilience may require engagement from the appropriate discipline, such as hydraulic engineers, coastal engineers, geotechnical engineers, and pavement engineers.

Marine vessels have lower adaptive capacity than road users to disruptions at coastal bridges. While cars and trucks may have alternate routes available, vessels might have to pass under the bridge to continue upstream. For example, in *Sandy: Yellow Mill Drawbridge,* passing under the bridge is the only way for marine traffic to access the local channel. If the bascule bridge is forced to remain closed due to damage from an extreme event, then vessels with air drafts exceeding the navigational clearance requirements under sea level rise and storm surge conditions will not be able to enter or exit the channel.

5.2. Coastal Hydraulics

This chapter describes some of the lessons learned from recent engineering assessments evaluating the vulnerability of transportation assets located along the coast to extreme events with climate change. These lessons could apply to transportation assets that are continually or occasionally exposed to coastal storm surge and waves. This includes the 60,000 miles of U.S. roads within the 100-year coastal floodplain and many of the 36,000 bridges within 15 nautical miles of the coast.[35]

5.2.1. Asset Sensitivities to Climate Change in the Coastal Environment

The level of damage caused by coastal storms in the past two decades—including Hurricanes Ivan (2004), Katrina (2005), Ike (2008), Irene (2011), and Sandy (2012)—makes it clear that some of our coastal transportation infrastructure is already highly vulnerable to extreme events today. Climate change is likely to increase this vulnerability (as outlined in one of this chapter's lessons learned below).

The primary critical coastal hazard considered in this chapter is extreme water levels due to storm surge, along with the associated waves/currents, and the influence of sea level rise on them. Global sea levels have been rising consistently as measured both by tide gages for the past 150 years and by satellites for the past 25 years. Projections for increasing rates of sea level rise are discussed in HEC-25 Vol 2[36] and summarized in section 4.

[35] FHWA, 2008.
[36] FHWA, 2014.

Other climate stressors have been considered in a number of the coastal assessments discussed in this chapter. These other climate stressors include possible changes in coastal storm frequency and strength, offshore wave heights, and coastal geomorphology. For example:

- The *Caltrans Pilot*[37] study considered bluff erosion along the northern California coast.
- The various *Gulf Coast Phase 2* studies considered the effect of stronger storms on storm surge in Mobile Bay.
- The *WFLHD/AKDOT&PF Pilot* study considered reduced sea ice levels and the resulting storm-induced erosion of a beach that protects a runway on the Chukchi Sea of the Arctic Ocean.

A complete listing of the case studies, assets, and climate change stressors is included in Table 7.

Waves on storm surge can damage coastal roadways, bridges, rails, and tunnels in a number of ways:

- Roadway damage by wave attack
- Roadway and railway damage by overwashing flow in storm surge
- Roadway damage by bluff erosion and shoreline recession
- Bridge deck damage by waves on surge
- Structure damage by wave runup
- Tunnel and road damage by overtopping

Inundation due to storms and sea level rise can also lead to loss of service and pavement integrity. The vulnerability of coastal transportation assets to these damage mechanisms will increase with climate change because the damage mechanisms are sensitive to sea levels and storm surge. More information on the above bulleted damage mechanisms can be found in HEC-25 Vol 2.[38]

5.2.2. Existing Guidance on Coastal Climate Adaptation

HEC-25 Vol 1 summarizes general engineering and planning guidance for coastal roads.[39] HEC-25 Vol 2 provides technical guidance for assessing the vulnerability of coastal transportation facilities to extreme events and climate change.[40] These assessments can range from broad planning overviews to highly detailed investigations employing state-of-the-art coastal modeling tools. HEC-25 Vol 2 suggests three “levels of effort” in determining the exposure of an asset to coastal storm hazards with sea level rise:

- **Level of Effort 1:** Use of existing (e.g., FEMA) inundation data and resources

[37] Throughout this section, case studies are referred to by an abbreviated title. For a full list of the case studies referenced in this report and their complete titles (with hyperlinks), see Appendix A: List of Case Studies.
[38] FHWA, 2014.
[39] FHWA, 2008.
[40] FHWA, 2014.

- **Level of Effort 2:** Original modeling of storm surge and waves for specific storm and sea level rise scenarios
- **Level of Effort 3:** Original modeling of storm surge and waves in a probabilistic storm risk framework with sea level rise projections

Many of the assessments discussed in this chapter used FHWA's HEC-25 Vol 2 manual or similar methodologies (Table 7). Most of these were "Level of Effort 1" studies in that they used existing flood inundation (FEMA) maps and added sea level rise to those elevations. The Level of Effort "2" and "3" studies used detailed hydrodynamic modeling of storm surge with sea level rise.

Table 7: Coastal Adaptation Case Studies

Study Name	Asset Type	Climate Change Stressor(s)	HEC-25 Vol 2 Analysis Level
GC2 Bridge Embankment-SLR	Bridge approach abutment	Sea level rise	1
TEACR Living Shoreline	Local Roadway	Sea level rise, waves on storm surge	1
TEACR Roadway Surge	Major Highway	Sea level rise, storm surge overwashing	1
Sandy: Governor's Island Ventilation Building	Tunnel Ventilation Building	Sea level rise	1
Sandy: Port Jersey Marine Terminal	Electrical Infrastructure	Sea level rise, storm surge	1
Sandy: Long Beach Road, NY	Major Highway	Sea level rise, waves on storm surge	1
Caltrans Pilot	Major Highway	Sea level rise, high ("king") tides	1
MTC Pilot	Roads, Transit Network, Toll Plaza, Bicycle/Pedestrian Networks	Sea level rise, waves on storm surge	1
GC2 Bridge Embankment – SLR	Revetment Protecting Bridge Approach	Sea level rise, waves	1
WFLHD/AKDOT&PF Pilot	Airport Runway	Sea level rise, waves, erosion	1
GC2 Navigable Bridge	Navigable waterway bridge	Sea level rise	1

Study Name	Asset Type	Climate Change Stressor(s)	HEC-25 Vol 2 Analysis Level
GC2 Highway Surge	Road alignment	Sea level rise, storm surge	2
GC2 Tunnel	Tunnel	Storm surge	2
GC2 Bridge-Storm Surge	Bridge segment/piers	Sea level rise, storm surge	2
GC2 Bridge Approach-Storm Surge	Bridge abutment	Sea level rise, storm surge	2
TEACR Coastal Bridge	Coastal Bridge	Sea level rise, waves on storm surge	2
GC2 Coal Terminal	Shipping Pier	Sea level rise, storm surge	2
MassDOT Pilot	Major Highway and Tunnel System	Sea level rise, waves and storm surge	3

5.2.3. Lessons Learned from Coastal Studies

Some very interesting and important lessons were learned through the process of assessing potential adaptation options for specific coastal assets. The lessons learned from these assessments are summarized in Table 8 and discussed further below. The lessons in Section 5.1 (Overarching Lessons Learned) are also highly relevant to coastal engineering and should be carefully reviewed.

TABLE 8: LESSONS LEARNED FROM COASTAL ENGINEERING ADAPTATION ASSESSMENTS

Lesson Category	Lessons Learned
Impacts on Infrastructure	Sea level rise will progressively make coastal transportation more vulnerable and less functional.
	Different types of coastal structures are inherently more or less sensitive to sea level rise.
	Sea level rise may have already contributed to damage of one major U.S. bridge during a hurricane.
Conducting Vulnerability Assessments	The Saffir-Simpson hurricane category scale is not appropriate for many coastal vulnerability assessments.
	The effect of sea level rise on peak storm surge levels can be non-linear.
	Original modeling of storm surge and waves is appropriate for major coastal projects.
	All appropriate engineering disciplines are needed for assessments of coastal assets.

Lesson Category	Lessons Learned
Developing Adaptation Measures	Coastal climate change adaptation measures will be similar to coastal engineering strategies for improving resilience to today's extreme weather events.
	Many coastal climate adaptation measures may be economically justified today as resilience measures, and the economic justification will increase as sea levels rise.
	Countermeasures and retrofits commonly suggested for bridges vulnerable to coastal storms may not be effective.
	A "living shoreline" can be a suitable climate adaptation measure for roadway protection.

Some of the lessons learned identified in this section have been widely recognized and discussed in the literature for decades but others have not. It has long been recognized that climate change will progressively make some transportation infrastructure more vulnerable and less functional (see Figure 10). These case studies simply reinforce this understanding with specific quantitative examples. However, the *TEACR Coastal Bridge* study found that many of the potential countermeasures commonly suggested for bridges vulnerable to coastal storms

FIGURE 10: SEA LEVEL RISE IS PROGRESSIVELY MAKING SOME COASTAL TRANSPORTATION INFRASTRUCTURE MORE VULNERABLE AND LESS FUNCTIONAL.

Photo credit: SCE.

will not significantly increase the resilience of the bridge studied. Instead, the bridge will fail from another mechanism, "negative-bending" of the bridge deck and girder, slightly later in the storm. The same study found that sea level rise may have already significantly contributed to the damage of one U.S. bridge during a hurricane. Both of these lessons learned are new findings that are not in the existing engineering literature.

5.2.3.1. Impacts on Infrastructure

Sea level rise will progressively make coastal transportation more vulnerable and less functional. This lesson learned is not new. It has been recognized for years concerning coastal infrastructure in general [41, 42, 43] and transportation infrastructure specifically.[44, 45, 46] Each of the TEACR coastal studies and many other transportation vulnerability assessments related to climate have quantitatively reinforced the general idea that sea level rise will make coastal infrastructure more vulnerable and/or less functional. For example:

- The *TEACR Coastal Bridge* study found that sea level rise will cause higher storm surges, higher wave-induced loads, and more potential damage to an Alabama bridge.
- The *TEACR Living Shoreline* study found that sea level rise will cause an escalating loss of service due to inundation for a local roadway in New York.
- The *TEACR Roadway Surge* study found that sea level rise will result in storm surge that reaches the threshold of the critical damage mechanism more frequently (from a 10-year event to a more frequent 5-year event).
- The *Sandy: Governor's Island Ventilation Building* assessment found that sea level rise will result in storm surge, during a storm similar to Hurricane Sandy in the future, flooding the Hugh L. Carey Tunnel (formerly called the Brooklyn Battery Tunnel) through the ventilation system.
- The *Sandy: Port Jersey Marine Terminal* assessment found that sea level rise will contribute to damage to critical electrical infrastructure by mid-century and proposed specific target elevations for raising the infrastructure.
- The *Sandy: Long Beach Road, NY* assessment found that sea level rise will cause progressively more flooding inundation of this arterial and evacuation route during extreme events.
- The *MassDOT Pilot* study found that sea level rise will increase the vulnerability of the major north-south corridor through Boston.

[41] National Research Council, 1987.
[42] IPCC, 1990.
[43] Melillo et al., 2014.
[44] Titus, 2002.
[45] Hyman et al. 2008.
[46] Kafalenos et al. 2008.

- The *Caltrans Pilot* study found that sea level rise will cause coastal roads along the state's northern coast, including US 101, to lose function more often and for longer durations in very high ("king") tides.
- The *MTC Pilot* study found that sea level rise will increase areas of coastal storm inundation near San Francisco Bay in Alameda County.

Different types of coastal structures are inherently more or less sensitive to sea level rise. The practical impact of moderate increases in exposure due to sea level rise can be significant in some cases for some types of rigid, fixed coastal structures (e.g., bridges and tunnel entrances) but less so for other types of more inherently flexible structures (e.g., rock revetments). The *GC2 Bridge Approach Embankment – SLR* study found that a rock revetment slope protection structure is not particularly sensitive to sea level rise. In contrast, the *TEACR Coastal Bridge* study found that the addition of 3 inches (essentially the amount of sea level rise since the time the bridge was designed) to critical storm surge heights of around 15 feet will add about 44,000 lbs. of wave-induced loads on the bridge decks. This is a significant increase relative to the failure capacity of the connections of that bridge in Alabama.

Sea level rise may have already contributed to damage of one major U.S. bridge during a hurricane. This unexpected lesson learned is an implication from the TEACR *Coastal Bridge* study, which assessed a bridge in Alabama. One of the study's conclusions also applies to another bridge, the I-10 Bridge over Escambia Bay, Florida, since the Florida bridge had a very similar design and was located on a similarly shallow bay about 60 miles (100 km) to the east of the Alabama bridge case study location. The Florida bridge was severely damaged during Hurricane Ivan in 2004 by wave-induced loads very similar to those evaluated in the Alabama bridge case study (see Figure 11). Extremely high storm surge levels allowed waves to strike the bridge decks, which were not designed for the large wave-induced loads. Ivan's storm surge levels just barely reached the height to move the Florida bridge decks before receding. Post-storm observations indicate that the critical damage threshold of wave-induced loads was not exceeded for parts of the bridge that were slightly higher in elevation or for parts of the bridge that were exposed to slightly lower wave heights (nearer shore or in the lee of the southern bridge span). Sea level rise between the time that the Florida bridge was originally designed (built in the 1970s) and 2004 may have been just enough to increase the wave-induced loads to cause the catastrophic failure. In other words, if sea levels had not risen in the three decades prior to Hurricane Ivan, the I-10 Florida Bridge may have survived the storm better. Further forensic engineering research on the performance of the Florida bridge during Hurricane Ivan could address this lesson learned more thoroughly.

FIGURE 11: SOME OF THE 2004 DAMAGE TO THIS INTERSTATE BRIDGE CAN BE ATTRIBUTED TO THE SEA LEVEL RISE THAT OCCURRED IN THE PREVIOUS DECADES (I-10; PENSACOLA, FLORIDA).

Source: Pensacola News Journal.

A second implication of the Alabama case study for the I-10 Florida Bridge is that the Florida bridge may have survived Hurricane Ivan if its design had included any of the adaptation or retrofit countermeasures evaluated in the assessment of the Alabama bridge. If the connections had been stronger, the additional strength probably would have allowed the bridge to survive long enough for the storm surge to recede as Hurricane Ivan passed (and it would not likely have failed by another mechanism). It should be noted that this implication is for the I-10 Florida Bridge and Hurricane Ivan only. As mentioned above, it appears that Ivan's storm surge just barely reached the elevation at which bridge decks began to be moved and then receded. However, the same is not true for the TEACR case study assessment of the I-10 Alabama Bridge with the selected storm scenario. In that scenario, the peak surge is much higher than the deck elevation and the potential wave-induced loads become much larger later in the storm.

5.2.3.2. Conducting Vulnerability Assessments

The Saffir-Simpson hurricane category scale is not appropriate for many vulnerability assessments because it is based on wind speed—not storm surge. Storm surge and waves/currents on the surge cause much of the damage to transportation infrastructure in hurricanes and it is well understood that storm surge at a specific site is more sensitive to the location and the track of the storm than the storm's wind "category." So, while laypersons often think of storm strength based solely on the "category" of storm, traditional risk-based design return-period analysis is more appropriate and was used for the vulnerability assessment in the *GC2 Coastal Tunnel* study.

The effect of sea level rise on peak storm surge levels can be non-linear. In other words, if the depth of flooding today in a storm = A and sea level rise = B, then the resulting future storm surge depth may be greater than A+B. This phenomenon introduces some inherent uncertainty in the commonly used approach of linearly adding an assumed sea level rise to peak storm surge elevations (a HEC-25 Vol 2, Level of Effort 1 Vulnerability Assessment).[47] The non-linear

[47] FHWA, 2014.

relationship between sea level rise and surge elevations was recognized in the *Gulf Coast Phase 2* study numerical modeling of storm surge with different assumed initial sea levels and identical storm and topography/bathymetry inputs. The degree of non-linearity is both site-specific (due to bathymetry/topography characteristics) and scenario-specific (due to storm characteristics). Future surge and waves will also be influenced by any vegetation changes and geomorphological changes, which occur as sea levels rise. Also, deeper water depths will result in larger storm waves at many coastal locations.

Original modeling of storm surge and waves is appropriate for major coastal projects. Conducting such modeling can be resource intensive, but the expense might be justified in the planning for major projects to ensure the expensive adaptation measures are precisely evaluated and tailored to the situation. Most climate vulnerability assessments are considered "Level of Effort 1" using the terminology outlined above from HEC-25 Vol 2 in that they use existing data and resources such as published inundation maps. The appropriate level of effort depends on the resources available and decisions required. Several case studies went beyond the basic existing exposure data sets and used original, high-resolution coastal engineering models. Examples of each level-of-effort study are:

1. The *WFLHD/AKDOT&PF Pilot* study is a good example of a complex "Level of Effort 1" study. The study used a number of standard coastal engineering tools and methodologies including a simple storm surge relationship, a parametric wind-wave generation model, a cross-shore sediment transport model, and a revetment stability model, along with available wave and water level climatology data. This approach was appropriate for the scope of this initial planning level study. More intensive modeling of wind fields and associated hydrodynamics of storm surge with sea level rise in the Chukchi Sea were recommended for informing the design of a specific project.
2. The *TEACR Coastal Bridge* study is a good example of a "Level of Effort 2" study. The study used information from high-resolution ADvanced CIRCulation (ADCIRC) modeling combined with outputs from a wave model (STWAVE) for one specific storm and sea level rise scenario. The model outputs were available from earlier work on the *Gulf Coast Phase 2* study. The approach was appropriate for this case because of the high value of the asset.
3. The *MassDOT Pilot* study is a good example of a "Level of Effort 3" study. The study assessed the vulnerability of the I-93 Central Artery/Tunnel system using a hydrodynamic model (including riverine flows, tides, waves, winds, storm surge, sea level rise, and wave setup) at a high enough resolution to identify site-specific locations that may require adaptation alternatives. The ADCIRC model was used to simulate these hydrodynamics because of its ability to accommodate complex geometries and bathymetries (see Figure 12). The team coupled ADCIRC with the Simulating WAves Nearshore (SWAN) model to simulate storm-induced waves in concert with the hydrodynamics. The model was used to develop estimates of the depth and probability of flooding at tens of thousands of locations along the Massachusetts coast in future

years. The risk-based probabilistic component of the analysis was appropriate for this major, critical asset in a heavily populated area.

All appropriate engineering disciplines are needed for assessments of coastal assets. Teams assessing the climate vulnerability of specific assets should include all of the appropriate engineering disciplines. The technical assessment team for the *TEACR Coastal Bridge* study included a structural engineer and a geotechnical engineer, in addition to coastal engineers. Having that full complement of specialty areas working together was particularly valuable and led to some of the lessons learned described above.

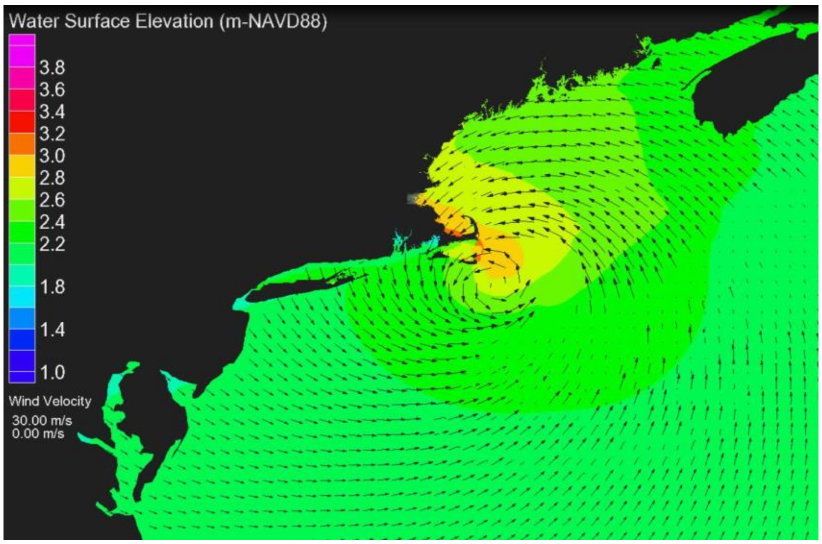

Figure 12: Original Modeling of Storm Surge and Waves Is Appropriate for Major Coastal Projects.

This is just one example of storm surge model output developed for assessing the vulnerability of Boston's Central Artery Project to the combined hazards of sea level rise and storms.

Source: *MassDOT Pilot* study.

Coastal engineering accounts for the planning, design, construction, and operation of infrastructure projects in the unique wave, water level, and sand transport environment along the coast. Coastal engineering makes extensive use of the sciences of nearshore oceanography and coastal geology, as well as geotechnical, environmental, structural, and hydraulic engineering principles. The design environment—the coastal water level, wave, and sand environment—is the primary factor distinguishing coastal engineering from other civil engineering disciplines. Meanwhile, the engineering component distinguishes coastal sciences from coastal engineering. A coastal engineer has both a formal education and experience in coastal engineering.[48]

Coastal engineers were actively involved in the assessment teams for most of the projects cited in this chapter. Most transportation engineering organizations include significant structural, hydraulic, and geotechnical engineering staff expertise; however, there are very few coastal engineers on staff in these organizations and thus few coastal engineers involved in teams doing coastal planning and engineering.

[48] FHWA, 2008.

5.2.3.3. Developing Adaptation Measures

Coastal climate change adaptation measures will be similar to coastal engineering strategies for improving resilience to today's extreme weather events. Many adaptation measures required for climate change and sea level rise are the same adaptation measures required for improving infrastructure resilience to extreme events with today's sea levels. Examples considered in these climate assessments include:

- The *TEACR Coastal Bridge* study concluded that increasing bridge deck elevation was the only adaptation strategy that ensured asset survival in the storm selected for the planning scenario. Increasing bridge deck elevation is the same strategy that was used in the southeastern United States to replace the bridges damaged in Hurricanes Ivan (2004) and Katrina (2005).
- The *TEACR Living Shoreline* study concluded that a traditional rock revetment, a living shoreline, or some combination of those approaches, would be a reasonable climate adaptation measure to protect the local road along a bay. The living shoreline approach was recommended based on lower costs and improved habitats.
- The *TEACR Roadway Surge* study concluded that the buried shoulder protection project built by the Florida DOT in 2006 (as a resilience improvement measure) is a viable climate adaptation measure considering future sea level rise (see Figure 13).
- The *GC2 Bridge Embankment – SLR* study found that the existing rock revetment slope protection will likely provide adequate protection under some sea level rise projection scenarios.

Figure 13: Coastal Climate Change Adaptation Measures Will Be Similar to Coastal Engineering Strategies for Improving Resilience to Today's Extreme Weather Events.

For example, this coast-parallel highway is now protected by a buried sheet-pile and rock structure (see concrete cap in left panel) under the pavement shoulder designed to prevent damage during hurricane overwashing (right panel).

Photo credit: SCE (left); FDOT (right)

- The *WFLHD/AKDOT&PF Pilot* study found that either a modified revetment or periodic beach repair (i.e., beach nourishment) will be able to protect an airport runway on the Chukchi Sea of the Arctic Ocean under future climate scenario assumptions. The local preference may, however, be relocation of the facility.

Many coastal climate adaptation measures may be economically justified today as resilience measures, and the economic justification will increase as sea levels rise. Much coastal transportation infrastructure is highly vulnerable to extreme events today. As a result, engineered resilience measures can often be economically justified today, with current sea levels and coastal storms. Sea level rise will increase vulnerability and thus, the economic justification for engineered resilience measures, as evidenced by the following studies:

- The *TEACR Roadway Surge* study concluded that a buried, shoulder protection project, which was built by the Florida DOT in 2006 at a cost of $15 million is economically justified with today's sea levels, and the economic justification increases when future sea level rise is considered. The annualized cost of the "roadway without protection" is 1.7 times the cost of the "roadway with protection" considering today's sea levels and storm climate. In other words, the cost of repeated replacement exceeds the cost of the protection project. This value multiplier increases from 1.7 to 4 when sea level rise is considered in a 50-year planning horizon.
- The *NJDOT Pilot* study found that much of the New Jersey coastal highway system is vulnerable to storm surge with today's sea levels. That finding was confirmed when Hurricane Sandy made landfall less than a year after the study was completed. Coastal engineering resilience measures are likely justified today and sea level rise will increase the justification.

Countermeasures and retrofits commonly suggested for bridges vulnerable to coastal storms may not be effective. The *TEACR Coastal Bridge* case study concluded that many of the potential countermeasures suggested after Hurricane Katrina for bridges vulnerable to coastal storms will not significantly increase the resilience of this bridge.

A variety of potential damage mechanisms were suggested and investigated in the aftermath of the 2004-2005 hurricanes. Eventually, most published investigations concluded that the primary damage mechanism was the lifting of the bridge deck off of the substructure due to wave-induced loads from the storm. Given this primary damage mechanism, alternative retrofit and countermeasure strategies often focused on strengthening the connection between the superstructure (the decks) and substructure.

Retrofit adaptation, which strengthens the connections between the superstructure and substructure, could be designed to avoid the primary, historical damage mechanism (separation of the decks from substructure). However, such adaptation measures alone would likely end in the destruction of the bridge due to another failure mechanism (i.e., deck-girder damage due to "negative-bending" and pile damage) slightly later in the storm. The engineering analysis in this case study found that only by increasing the bridge elevation would bridge failure be avoided.

This finding was the result of considering the load path through the structure from the structural engineering perspective. Thus, an alternative way to state this lesson learned is: "follow the load path" through the structure (which is standard structural engineering practice). Following the load path implications through the entire structure is required in the design of engineering adaptation for coastal bridges exposed to wave-induced loads on storm surge.

A "living shoreline" can be a suitable climate adaptation measure for roadway protection. The *TEACR Living Shoreline* case study found that a living shoreline approach could provide protection for Shore Road in Brookhaven, NY (see Figure 14). So-called "green" infrastructure, or "natural and nature-based" engineering approaches, like living shorelines, have the potential to reduce the exposure of Shore Road to wave action now and with future sea level rise.

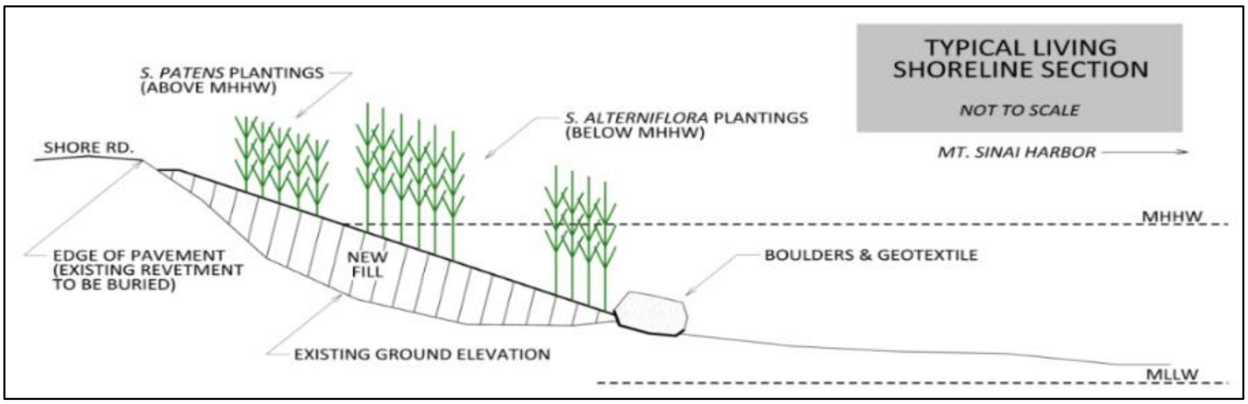

Figure 14: "Green" Infrastructure, Such as a "Living Shoreline," Can Be a Suitable Climate Adaptation Measure for Roadway Protection When Designed Properly and Used Appropriately.

Source: *TEACR Living Shorelines* study.

A living shoreline is generally defined as an alternative for shoreline stabilization that uses natural and organic materials that complement the natural shoreline while providing suitable habitat for local species. A living shoreline can be a preferred alternative to traditional shoreline armoring when designed properly and used appropriately, particularly along sheltered shorelines like Shore Road. A living shoreline may include a combination of an engineered structure to attenuate wave energy, appropriate vegetation, and sand to stabilize the shoreline and provide nearshore habitat for native species of flora and fauna. The design of a living shoreline is an evolving application of coastal engineering, coastal science, and coastal ecology.

5.2.4. Adaptation Strategies to Increased Coastal Threats

This section discusses the possible adaptation strategies that were considered in the specific assessments discussed above. Adaptation strategies may be broadly categorized as follows:

- **Manage and maintain—**Strategies designed to maintain existing infrastructure for optimal performance and manage the response to extreme events through advanced preparation.
- **Increase redundancy—**Strategies designed to ensure that transportation services provided by infrastructure can be supplied by other means/alternatives.
- **Protect—**Strategies designed to reduce or eliminate damage by providing protective physical barriers to climate stressors and extreme events.
- **Accommodate—**Strategies designed to modify or redesign infrastructure to better coexist in a climate-stressed environment.
- **Relocate—**Strategies designed to lessen or eliminate exposure to climate stressors by relocating infrastructure away from the coastline.

Combinations of these strategies may also be employed. Some of the pros and cons of the asset-specific adaptation strategies are summarized in Table 9. While these lessons learned are unique to these specific locations and assets, a reader interested in similar adaptations or with questions about these pros and cons can read the corresponding detailed case studies.

Table 9: Potential Adaptation Strategies Investigated in the Coastal Case Studies

Adaptation Category	Asset-Specific Strategy	Pros	Cons	Case Studies with More Information
Maintain and Manage	Maintain existing protection systems (e.g., riprap)	No substantial changes to existing protections Maintains current design standards	May be insufficient under future climate conditions	*GC2 Bridge Embankment-SLR*
	Reroute traffic in extreme events	Can be implemented immediately with pre-planning Low cost	Operational issues and loss of function have costs May not be appropriate for critical routes	*WSDOT Pilot*
Increase Redundancy	Build an alternative access route at a higher elevation and thus a higher resilience level	Maintains access to critical facilities during extreme events	Cost of building an alternative access road	*Sandy: Bergen Avenue, NY* ($)
Protect	Revetment/seawall along coastal roadway to prevent wave damage	Would protect asset under climate scenarios Well understood design and construction methods	Can have negative impacts on beach and beach access	*TEACR Living Shoreline*
	Living shoreline to prevent wave damage	Would protect asset under climate scenarios Preserves more natural coastal habitat Can be more cost-effective than revetment	Typically limited to short-fetch situations along sheltered shorelines May be additional permitting challenges in some states	*TEACR Living Shoreline* ($)
	Buried shoulder protection along roadway to prevent overwashing damage	Will protect asset under climate scenarios	Additional initial capital costs Some post-storm sand replacement may be needed	*TEACR Roadway Surge* ($)

Adaptation Category	Asset-Specific Strategy	Pros	Cons	Case Studies with More Information
		Economically justified with today's sea levels and more so with future sea level rise		
	Periodic beach nourishment or sand dune construction to prevent wave damage	Reduces frequency of overwashing and provides small reservoir of sand, which buries the road early in the storm reducing damage in some situations Costs can be justified by reduced future damages over the life of the project	Adequate local sand sources may be problematic	*WFLHD/AKDOT&PF Pilot TEACR Living Shoreline*
Accommodate	Modified revetment to prevent wave damage	Would protect asset under climate scenarios	May not be the preferred local option	*WFLHD/AKDOT&PF Pilot*
	Increasing coastal bridge deck elevation to prevent damage from waves on surge	Has proven successful as a coastal extreme event resilience approach for new construction Would protect bridge asset from climate hazards	Lower approach spans still vulnerable Cost typically high	*TEACR Coastal Bridge*
	Building coast-parallel roads at lower elevations farther back on barrier islands	Can result in burial under sand early in storm, which reduces pavement damage	Can be high property costs and valuable wetland habitats May be increasing exposure as sea levels rise	*HEC 25 Vol 2*
	Strengthen connections on coastal bridge to prevent damage from waves on surge	May provide slight increase in extreme event and climate resilience	Will likely lead to failure by another damage mechanism, "negative-bending" slightly later in storm	*TEACR Coastal Bridge*

Adaptation Category	Asset-Specific Strategy	Pros	Cons	Case Studies with More Information
	Modify bridge cross-section to prevent damage from waves on surge	Possible reductions in wave-induced loads are theoretically possible	No guidance available for design as this is a research need/knowledge gap	*TEACR Coastal Bridge*
	Install flood gates over tunnel entrances	Can protect against any storm level	Operational issues closing the gates before storm arrival	*GC2 Tunnel*
	Raise tunnel approach walls and/or include breakwater/berm to reduce wave runup and overtopping	Reduces the risk of flooding of tunnel	May be a limited improvement in risk reduction	*GC2 Tunnel*
Relocate	Abandon local coast-parallel road to prevent wave damage	Allows natural processes to resume Costs can be justified by reduced future damages over the life of the project Coast-perpendicular roads can be used to access certain coastal points of interest	May not be possible due to legal reasons	*TEACR Living Shoreline*
	Relocate asset to avoid wave damage	May be locally preferred option	Cost may be high	*WFLHD/AKDOT&PF Pilot*

5.2.5. Coastal Knowledge Gaps

Research is needed on quantitative methodologies for coastal damage mechanisms. Research is needed to develop improved methodologies for quantifying the sensitivity of transportation assets to damaging coastal processes. This is essentially a call for more research into the mechanisms (loads, scour, etc.) that cause the transportation infrastructure damage and the related important issues of quantifying levels of damage from the exposure metrics (e.g., depth-damage curves). Damage to the asset will depend on the actual failure mechanism (e.g., wave loads on bridge decks, embankment damage by flowing water, etc.), as well as the duration of the event, the cumulative impacts of multiple events, and the condition of the structure (i.e., the loads and resistance). One specific example from the *TEACR Coastal Bridge* study is a lack of basic knowledge allowing for design of a possible adaptation of changing the traditional cross-sectional shape of coastal bridges to reduce wave-induced loads. Unfortunately, at this time the existing design methodologies are not available to pursue such a logical adaptation approach. A similar related issue is the expected reduction in wave-induced loads on bridge decks at high levels of submergence (reducing the elevation to improve resilience). Existing design methodologies are not developed well enough.

Research is needed on the (non-linear) relationship between sea level rise and future extreme event storm surge levels. The storm surge modeling from the GC2 study (results were used in the *TEACR Coastal Bridge* study) showed that there is not a 1:1 relationship between future sea level rise and increases in likely future extreme levels of storm surge. In other words, one foot of sea level rise can result in more than one foot of additional storm surge in the 100-year storm. There is currently very little guidance available about this non-linearity and most of the existing published documentation comes from studies in the Gulf of Mexico. This is an area of research that needs more attention. Most vulnerability assessments are “Level of Effort 1” under the HEC-25 Vol. 2 methodology, and could benefit from a simple multiplicative factor approach to account for this non-linear effect while using existing storm surge elevation data (e.g., FEMA maps).

Further understanding of the 2004 Florida bridge damage, considering sea level rise, is needed. The potential that sea level rise has already contributed to significant damage to a U.S. bridge is an important, unexpected finding of the *TEACR Coastal Bridge* study. A forensic engineering reanalysis of that damage event, which includes consideration of sea level rise between the time the bridge was designed (1970s) and 2004, is warranted.

The development of nationwide, highly resolved, risk-based surge and wave climatology is needed. The USACE North Atlantic Coast Comprehensive Study provides excellent coastal engineering data for project vulnerability assessments and design. Development of similar data for the rest of the nation would be valuable.

5.3. Riverine Flooding

This chapter is a discussion of lessons learned from a series of case studies focused on evaluating impacts to highway assets from riverine flooding sources, related watershed processes, and other factors that influence the hydrologic cycle. The range of assets that could be impacted by changes in precipitation and associated flooding is broad; discussions in this chapter are limited to those assets addressed in these recent case studies.

The climate change stressors addressed in this chapter are precipitation-driven flooding and the combination of wildfire followed by heavy precipitation.

5.3.1. Asset Sensitivities to Climate Change in the Riverine Environment

Figure 15: Pavement Failure After Flooding on US-101 South of Gold Beach, Oregon.
Source: *ODOT Pilot* study.

Changes in precipitation and the resultant changes in stream flows are the primary climate change stressors expected to impact transportation assets in the riverine environment. Climate change projections of precipitation vary across geographies, models, and timeframes. In some locations annual precipitation is projected to increase (e.g., the northern US) and in others (e.g., the Southwest) it is projected to decrease; in many cases, whether or not precipitation will increase or decrease on an annual basis, future projections of precipitation indicate that rainfall events will be heavier when it *does* rain.[49] Climate change influences on extreme event precipitation represent a threat to transportation infrastructure because increasing trends in extreme event precipitation may cause increasing flood flows and associated increases in flood water elevation at river crossings. These changes in precipitation could result in more frequently flooded roadways and changes in channel stability (see Figure 15).

The following subsections discuss how different types of transportation infrastructure could be affected by climate-change induced changes in precipitation and wildfire.

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[49] Walsh, et al., 2014 states in the National Climate Assessment that "Although … changes in overall precipitation are uncertain in many U.S. areas, there is a high degree of certainty that the heaviest precipitation events will increase everywhere, and by large amounts. This consistent model projection is well understood and is a direct outcome of the increase in atmospheric moisture caused by warming."

5.3.1.1. Bridge/Culvert Sensitivities to Climate Change in the Riverine Environment

Engineering practitioners follow design standards to design bridges and culverts on a case-by-case basis; the individual performance of a structure is determined by multiple factors including surrounding hydrology, topography and geology, bathymetry, roadway elevation relationship to river valley, environmental constraints (e.g., the need for fish or aquatic organism passage), and economic and regulatory considerations.

Riverine threats to culverts and bridges could include overtopping and flooding of travel lanes, channel instability, aggressive channel migration, and channel bed aggradation. Each of these threats is discussed in more detail below.

Overtopping and Flooding of Travel Lanes

Roadway overtopping is expected to occur over the design life of many culvert and bridge structures, however, it can still be considered a form of impairment when it leads to flooding of roadway travel lanes and loss of service (see Figure 16). However, in cases where overtopping frequency and flow depths are expected to increase due to the projected climate change precipitation events, additional impacts beyond loss of service could occur along the overtopped section of road. The case study research teams included increases in the following impacts of roadway overtopping in their studies:

- Debris buildup on the roadway travel lanes.
- Erosion of roadway embankments due to supercritical flow conditions on the downstream slopes.
- Damage to bridge rails and parapets due to debris clogging and increased lateral forces.
- Loss of roadway pavement (starting at the shoulders) due to roadway embankment erosion.
- Loss of roadway pavement due to hydraulic uplifting.

FIGURE 16: IA-1 FLOOD DAMAGE NEAR MOUNT VERNON, IOWA.

Source: *IDOT Pilot* study.

- Breaching of roadway embankments due to progressive embankment erosion.
- Loss of life due to vehicles swept away by floodwaters or crashing into roadway breach.

Destabilization of Stream Conditions and Channel Bed Aggradation

In the *TEACR Culvert*[50] study the FHWA research team considered the impacts of increased heavy precipitation and wildfires due to climate change on stream geomorphology. The team evaluated the sufficiency of the stream channel and culvert crossings to handle bed load sediment transport and debris flow conditions under post-wildfire conditions. Droughts and subsequent wildfires can have a significant impact on watershed response through both increased runoff and accumulation of debris. Both are expected to increase in frequency and intensity with climate change in some areas.

FIGURE 17: POST-WILDFIRE CHANNEL BED AGGRADATION, JOHN DAY, OREGON.

Photo credit: US Forest Service.

Under post-wildfire conditions, debris flows are caused by increases in upland erosion due to the complete loss of protective vegetative cover and other burn impacts. The FHWA *TEACR Culvert* research team focused on the ability of the stream and the study site culvert to convey debris flows created by upland wildfires. In the study, the potential deposit of the debris flows or bed load materials would clog or otherwise reduce the capacity of the study site culvert, causing further decreases in system performance and more frequent overtopping of the roadway. Similar stream geomorphology/bed load transport concerns have also been noted for culvert and bridge study sites in western states where mountain rivers and glacial outflows can produce significantly elevated bed load levels that deposit and aggrade stream channel beds (see Figure 17).

5.3.1.2. Road Sensitivities to Climate Change in the Riverine Environment

Flood sensitivities and damage mechanisms for roads within floodplains are similar to the mechanisms described for bridges in overtopping and flooding of travel lanes (see Section 9.0).

The *MnDOT Pilot* research team performed a vulnerability study that concluded that approximately 50 percent of the studied roadways had a medium to high vulnerability to climate change, primarily due to overtopping risks.

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[50] Throughout this section, case studies are referred to by an abbreviated title. For a full list of the case studies referenced in this report and their complete titles (with hyperlinks), see Appendix A: List of Case Studies.

5.3.2. Existing Guidance on Riverine Climate Adaptation

In 2016, FHWA published the second edition of HEC-17 as a technical manual on assessing the exposure and vulnerability of highway infrastructure to flooding. The manual supports project delivery for planning, design, maintenance, and operations for transportation facilities and networks within the river environment and contains the best currently available science, technology and information from FHWA on floodplains, extreme events, climate change, risk, resilience, and uncertainty. Examples of potential analysis methods are documented in various FHWA-funded pilot case studies.

The second edition of HEC-17 also introduces an analysis framework for performing risk and vulnerability assessments of riverine transportation infrastructure. The framework presents five different levels of analysis in recognition of the need for varied levels of effort, depending on the relative importance of an individual piece of infrastructure.

- **Level 1 – Historical discharges.** At level 1, the design team applies standard hydrologic design techniques based on historical data to estimate the design discharge. In addition, the design team qualitatively considers changes in the estimated design discharge based on possible future changes in land use and climate.
- **Level 2 – Historical discharges/confidence limits.** At level 2, the design team estimates the design discharge based on historical data and qualitatively considers future changes in land use and climate as in level 1. In addition, the design team quantitatively estimates a range of discharges (confidence limits) based on historical data to evaluate project performance.
- **Level 3 – Historical discharges/confidence limits with precipitation projections.** At level 3, the design team performs all level 2 analyses and quantitatively estimates projected changes in precipitation for the project location. The design team evaluates the projected changes in precipitation to determine if a higher level of analysis (using climate projections) is appropriate.
- **Level 4 – Projected discharges/confidence limits.** At level 4, the design team completes all level 3 analyses and develops projected land use and climate data, where feasible. The design team performs hydrologic modeling using the projected land use and climate data to estimate projected design discharges and confidence limits.
- **Level 5 – Projected discharges/confidence limits with expanded evaluation.** At level 5, the design team performs the equivalent of the level 4 analyses based on custom projections of land use and climate. The design team also expands to include appropriate expertise in climate science and/or land use planning to secure site-specific custom projections.

The HEC-17 framework is proposed for application to both specific study sites and to system-wide studies that may include multiple hydraulic structures.

The case studies listed in Table 10 provide examples of potential methods for incorporating climate change into the engineering design process. These pilot case studies also provided the findings and insights highlighted in this chapter. Hyperlinks to the complete case studies are included in the table. For more information on any of these studies, please review the full case study reports.

TABLE 10: RIVERINE ADAPTATION CASE STUDIES

Study Name	Asset Type	Climate Change Stressor(s)	HEC-17 Analysis Level
CTDOT Pilot	Bridge and culvert structures six feet to 20 feet in length	Precipitation	1
GC2 Culvert	Four cell concrete box culvert	Precipitation	4
IDOT Pilot	Six bridges	Precipitation	5
MnDOT Pilot	Bridges, large culverts, pipes, and roads paralleling streams	Precipitation	4
NYSDOT Pilot	Culverts (various sizes and dimensions)	Precipitation	3
TEACR Culvert	Twin cell concrete box culvert	Precipitation; wildfire	4
WSDOT Pilot	Highway segments	Precipitation	2

5.3.3. Lessons Learned from Riverine Studies

The research teams for each of the riverine climate adaptation studies highlighted many lessons learned during their research and documentation. These cross-cutting lessons from the studies are grouped and summarized in Table 11. The table is followed by more detailed information on each of the lessons, including examples from the individual studies. The lessons in Section 5.1 (Overarching Lessons Learned) are also highly relevant to riverine situations and should be carefully reviewed.

TABLE 11: LESSONS LEARNED FROM RIVERINE ENGINEERING ADAPTATION ASSESSMENTS.

Lesson Category	Lessons Learned
Appropriate Use of Future Precipitation Projections	If climate models predict decreases in extreme event precipitation under future narratives, then current conditions will control project designs.
	The use of 24-hour duration precipitation projections from climate models are better suited for the analysis of larger watersheds.

Lesson Category	Lessons Learned
Use of Historical Data in Adaptation Analyses	When evaluating infrastructure using historical precipitation data sets, engineers should consider a range of flow events beyond the standard design storm.
Use of Rainfall/Runoff Modeling in Climate Adaptation Studies	Rainfall/runoff models (as opposed to regression-based approaches) are better suited to incorporating future precipitation projections, but they require more detailed knowledge of corresponding rainfall patterns and the response of the watershed to those patterns over an extended period of time.
	In larger watersheds, peak storm flow response may not linearly follow trends in climate change precipitation as increases in peak flows may be more dependent on the watershed characteristics and dynamic response to precipitation than on an increase in precipitation alone.
Understanding the Resiliency of Existing Facilities	Hydraulic performance curves can help illustrate the existing resilience, or lack thereof, of an asset under various flow scenarios.
Wildfire Impacts and Adaptation	Wildfire burn of a watershed causes a dramatic increase to storm flows and creates the potential for debris flows.
	Due to the short time horizon of wildfire impairment to a watershed, the risk of occurrence of extreme storm flows is lowered; therefore, lower design storm conditions may be appropriate for post-fire designs.
	Reactive adaptation of culverts to wildfires is economically justifiable due to the relatively low probability of wildfire occurrence combined with the high cost of culvert upsizing.
	Wildfire debris flows threaten riverine infrastructure by bulking (increasing) storm flow rates and by increasing the risk of debris clogging/aggradation of the river channel.

5.3.3.1. Appropriate Use of Future Precipitation Projections

If climate models predict decreases in extreme event precipitation under future narratives, then current conditions will control project designs. The *TEACR Culvert* study, for instance, predicted decreases in extreme event precipitation for two of the three climate simulations analyzed. In these situations, assets should not be designed for projected decreases in precipitation because the assets still need to withstand current-day conditions.

The use of 24-hour duration precipitation projections from climate models are better suited for the analysis of larger watersheds. The uncertainties in projections of future precipitation patterns increase as the temporal/spatial resolution is refined through downscaling processes. In the second edition of HEC-17, FHWA recommends using downscaled daily climate projections from the DCHP database (see the Chapter 4 on climate data for more information). Most of the research teams in the case studies worked with future precipitation projections, but had differing opinions about where projected precipitation data could be used appropriately. In general, each research team determined that watershed size was a key consideration when determining the appropriate use of future precipitation values. While large watershed modeling can use 24-hour duration precipitation projections to accurately model rainfall and runoff processes, smaller watershed modeling may require shorter duration precipitation data since the total duration of extreme events is shorter in smaller watersheds. Engineering practitioners should consider the characteristics of a watershed (such as flow timing) and the ability to calibrate existing conditions rainfall / runoff models against available streamflow data using 24-hour duration precipitation before proceeding with use of the data for a watershed climate adaptation study.

FIGURE 18: FLOODING OF I-80 BY THE CEDAR RIVER NEAR IOWA CITY, IOWA.

Source: *IDOT Pilot* study.

The IDOT study team provided a detailed investigation on the appropriate use of 24-hour duration projected climate change precipitation data in large watersheds. In the study, the IDOT team ran tests on historical data to determine if the coarse temporal/spatial gradation of the climate data significantly changed the peak flow results compared to the fine gradations associated with real precipitation and stream gage data. The IDOT team found that for the larger watersheds the coarse climate projections were nearly just as accurate at producing peak flows as the rich historical data. This provided an additional level of confidence with the results that helped IDOT to justify its adaptation decisions for the six bridges that were analyzed.

5.3.3.2. Use of Historical Data in Adaptation Analyses

When evaluating infrastructure using historical precipitation data sets, engineers should consider a range of flow events beyond the standard design storm. While the design standard for evaluation of infrastructure will remain constant, the flood flow input to that design standard could shift in the future. In the *CT DOT Pilot* study, the research team evaluated the excess capacity of existing culverts to help determine the future resilience of each piece of infrastructure. Study teams working to incorporate climate change models will need to consider a range of flow events beyond the design standard due to the wide range of potential future conditions, particularly for assets with long remaining service lives.

5.3.3.3. Use of Rainfall/Runoff Modeling in Climate Adaptation Studies

Rainfall/runoff models (as opposed to regression-based approaches) are better suited to incorporating future precipitation projections, but they require more detailed knowledge of corresponding rainfall patterns and the response of the watershed to those patterns over an extended period of time. Rainfall/runoff models are theoretical based representations of watershed runoff processes that predict streamflow rates based upon specified precipitation / rainfall amounts and varied watershed physical properties (e.g., drainage area size, land cover, watershed timing). Probabilistic, regression-based approaches have advantages over a rainfall/runoff models that include ease of use and inherent consideration of regional conditions in flood predictions. Conditions such as storm characteristics, overland flow characteristics, and general topography are inherently included in development of regression equations and do not need to be computed individually for each watershed being studied. However, the inclusion of precipitation as a dependent variable in the development of most regression equations, does not readily allow for consideration of non-stationarity and projection of future storm flow conditions. The *GC2 Culvert* and *TEACR Culvert* studies both provide examples on the use of rainfall/runoff models to predict future storm flow rates based upon climate model precipitation amounts, while still including valuable information from regression equations in the model calibration process.

In larger watersheds, peak storm flow response may not linearly follow trends in climate change precipitation as increases in peak flows may be more dependent on the watershed characteristics and dynamic response to precipitation than on an increase in precipitation alone. In the Midwest, river floods can persist for days or weeks in river basins with gently sloping landscapes because the large basins drain slowly, creating an extended period over which rainfall can feed into a flood pulse in the river system. This complicated rainfall and streamflow timing mechanism was most likely responsible for the 2008 Cedar Rapids, Iowa, flood that exceeded 1.4 times its 500-year interval flood and closed Interstate-80 for several days (see Figure 18 and Figure 19).

To address this issue, the *IDOT Pilot* research team developed an analysis approach that integrated climate projections of future rainfall with a dynamic watershed/river system model to project flood response to climate change on larger river systems. The *IDOT Pilot* team obtained historical data on annual peak flows and daily precipitation, and then compiled daily precipitation

FIGURE 19: FLOODING OF I-80 NEAR CEDAR RAPIDS, IOWA.
Source: *IDOT Pilot* study.

data from 19 climate model projections. The team compiled the precipitation data and entered it into the CUENCAS hydrological model (a two-dimensional distributed rainfall/runoff hillslope model) to generate projected future daily stream flows. The team used the CUENCAS model to demonstrate the conveyance of the river flows downstream to six bridge study sites, then contrasted the flood data and river crossing performance with and without future climate change at the study sites to determine vulnerability due to climate change. By simulating future continuous daily stream flows, the *IDOT Pilot* research team was able to better evaluate multiday duration peak flows reflecting the ground/surface water balance and slow response times of the large, mild-sloped watersheds.

5.3.3.4. Understanding the Resiliency of Existing Facilities

Hydraulic performance curves can help illustrate the existing resilience, or lack thereof, of an asset under various flow scenarios. Because each piece of drainage infrastructure may have a different sensitivity to a change in precipitation, using a performance curve (stage versus flow) analysis method can help to visualize the resilience that a piece of infrastructure may already have. The *CT DOT Pilot* created performance curves of their culverts to show where some culverts—which may have been installed under higher fills or which may have been more than adequate hydraulically due to minimum diameter requirements—had a high degree of resilience or ability to handle more flow without violating design criteria or causing a structural failure. Steeply sloped streams with narrow floodplains are generally more prone to flooding than mild-sloped streams with wider floodplains, which can absorb more flow without significant changes in depth and velocity. However, each asset site is unique, with different design criteria and controlling factors such as downstream tailwater conditions, adjacent private property to protect, and environmental permit requirements such as outlet velocities. Performance curves can illustrate these site-specific constraints and make it easier to make adaptation decisions.

5.3.3.5. Wildfire Impacts and Adaptation

Wildfire burn of a watershed causes a dramatic increase to storm flows and creates the potential for debris flows. Wildfires may become more frequent in some regions under a changing climate due to increased temperatures, periods of drought, and the greater potential for insect infestations. Wildfires impair the hydrologic processes within a watershed by defoliating the area and hardening the soils against infiltration (hydrophobicity). Stormflows are increased as the vegetative interception of precipitation is lost, infiltration of surface runoff is minimized, and overland flow of water is no longer impeded by grasses and woody plant roots.

Debris flows are caused by increases in upland erosion and mobilization of the burned-out remains of trees (see Figure 20). Upland erosion increases as precipitation directly strikes the soil without energy loss to plant cover, allowing for soils to become dislodged and for overland flow energy to increase without flow impedance by grasses and woody roots. Due to these factors, the FHWA *TEACR Culvert* study demonstrated that the combined impacts of increased stormflows and debris flows could cause a five-year precipitation event to produce a flood event greater than the unimpaired 100-year event.

FIGURE 20: POST-WILDFIRE DEBRIS FLOW DEPOSITS ON A ROADWAY, CALIFORNIA.

Photo credit: US Forest Service.

Due to the short time horizon of wildfire impairment to a watershed, the risk of occurrence of extreme storm flows is lowered; therefore lower design storm conditions may be appropriate for post-fire designs. Studies collected and referenced by the FHWA team in the *TEACR Culvert* study have shown that wildfire burn impairments last from five to 10 years, with some level of watershed healing starting within two years of the burn. The impairments start to heal as grasses germinate within the burned soils and break the hardened soil surface, thus boosting infiltration and providing resistance to overland flows. Further healing occurs as woody shrubs and trees start to repopulate the watershed.

Given that the impairment period for the watershed is significantly less than the design life of the infrastructure, the probability of an extreme event occurring within the impairment period is low. Consideration of smaller storm events for the design of post-wildfire infrastructure may be appropriate if the risk of the smaller storms occurrence during the short impairment period is similar to the risk of a larger storms occurrence over the longer design life (e.g., the risk of a 10-year storm occurring over a 10-year wildfire impairment period is similar to the risk of a 100-year storm occurring over a 100-year design life for a culvert).

Reactive adaptation of culverts to wildfires is economically justifiable due to the relatively low probability of wildfire occurrence combined with the high cost of culvert upsizing. The TEACR Culvert study team was unable to accurately determine the probability of wildfire occurrence in their study watershed, but were able to conclude that the probability is relatively low (in the range of 0.3 over a 100-year period). The TEACR Culvert study did include analyses of various adaptation costs and concluded that proactive upsizing of culverts in advance of a wildfire event would be significantly expensive. When considering the numerous amount of culvert crossings in any state's roadway network, the compound cost of proactive culvert adaptation will significantly exceed program needs for reactive approaches to wildfire adaptation. Thus, careful consideration should be given to upsizing proposed new or reconstructed infrastructure as a proactive protective measure for unburned watersheds. However, in critical locations design practitioners should consider the possibility of wildfire occurrence and incorporate flexibility for future adaptation of the infrastructure when developing a course of action.

Wildfire debris flows threaten riverine infrastructure by bulking (increasing) storm flow rates and by increasing the risk of debris clogging/aggradation of the river channel. Debris flows from a post-wildfire watershed are a mixture of sediment and remnant woody vegetation (see Figure 21). Debris flows increase or "bulk" the total clear water peak flows by combining with storm flows to create hyper-concentrated sediment slurry stream flows. The *TEACR Culvert* study determined that addition of the debris could bulk stream peak flow rates by a factor of 1.6 to 2.2 above the water-only flow rates.

FIGURE 21: POST-WILDFIRE DEBRIS FLOW DEPOSITION, JOHN DAY, OREGON.

Photo credit: US Forest Service.

Beyond the peak flow bulking concerns, debris clogging and aggradation can become a serious concern for infrastructure in conditions where decreases in stream flow energy cause sediment to drop out of the hyper-concentrated slurry. The design of wildfire adaptation options requires understanding of these interactions and solutions that maintain necessary stream flow energy, as a single storm debris flow can completely clog an undersized piece of riverine infrastructure.

5.3.4. Adaptation Strategies to Increased Riverine Threats

For many of the case studies, the research teams developed adaptation strategies to address the projected impacts of climate change on the subject infrastructure. Table 12 provides a summary of the adaptation strategies considered by the research teams. Although the strategies developed by the research teams are by no means exhaustive, they do represent the types of actions that could be considered by other practitioners.

In addition to presenting potential adaptation options, Table 12 provides information on the benefits and drawbacks of the adaptation strategies, which may influence the selection of a particular strategy in a given location. In the table, the adaptation strategies are grouped to provide insight into the core types of actions that may be useful to increase resilience:

- **Increase Peak Flow Capacity**—Strategies designed to increase the ability of the culvert or bridge to pass current and future peak water flows safely under the roadway.
- **Watershed restoration/repair**—Strategies and stormwater management actions that manage and decrease future peak flow rates through a watershed-based approach.
- **Protect**—Strategies designed to reduce or eliminate damage by providing protective physical barriers to climate stressors and extreme events.
- **Relocate**—Strategies that move the asset outside of the projected flood exposure area. Such strategies include elevating the roadway or moving it to another location.

TABLE 12: POTENTIAL ADAPTATION STRATEGIES INVESTIGATED IN THE RIVERINE CASE STUDIES

Adaptation Category	Adaptation Strategy	Pros	Cons	Case Studies with More Information*
Increase peak flow capacity	Replace culvert with a bridge	Increases capacity to transport water and sediment/debris Improves fish passage	May move flooding issues downstream Expensive and may require additional right-of-way (ROW) Scour-based design required for bridge foundation Additional maintenance and inspection costs	*TEACR Culvert ($)* *GC2 Culvert ($)* *MnDOT Pilot ($)*
	Replace existing culverts with larger culverts	Increases capacity to transport water and sediment/debris Relatively quick construction time Relatively low capital cost	May move flooding issues downstream May allow sediment buildup during larger storms Larger culverts may require inspection	*TEACR Culvert ($)* *GC2 Culvert ($)* *MnDOT Pilot ($)* *NYSDOT Pilot*
	Retrofit facility to increase the number of culvert cells	Relatively low capital cost Relatively short construction time	May move flooding issues downstream Flow capacity increase limited compared to a bridge opening Larger culverts may require inspection	*TEACR Culvert ($)* *GC2 Culvert ($)* *MnDOT Pilot ($)*
Watershed restoration/repair	Implement regional drainage area management—consider the entire drainage area and determine how best to manage drainage	Could help reduce flooding risks over a larger geographic area	A large-scale plan could have a lengthy implementation timeline and be costly Current permitting frameworks do not generally support this strategy Treatment is likely to occur outside of DOT-owned ROW	*GC2 Culvert*

Adaptation Category	Adaptation Strategy	Pros	Cons	Case Studies with More Information*
	Implement dispersed stormwater and debris controls throughout watershed	Helps reduced flooding and / or debris flow risk at selected infrastructure sites. Reduces flooding and / or debris flow risk to property or infrastructure downstream of the selected site. More readily permittable over regional stormwater facilities. Additional long-term water quality benefits are possible	Requires substantial property for implementation. Case study implementation shows this to be a costly option. Will require significant long-term maintenance commitments on the part of the owner	*TEACR Culvert ($)*
	Stream restoration and floodplain enhancement—creation of low floodplain bench areas for flood distribution	Can be a localized treatment technique (may be able to occur within DOT-owned ROW) Provides additional benefits to water quality/stream habitat conditions Lowers velocity and stress conditions at the structure With proper application, will lower peak flood elevations	Significant grading footprint required to achieve necessary floodplain areas for peak flow rate attenuation Most effective application of strategy may require work outside of existing DOT-owned ROW Long-term maintenance over a large stream area may be required	*MnDOT Pilot ($)*
Protect	Retrofit of existing flood control infrastructure (e.g., dams) to provide added capacity	Lower cost than construction of new infrastructure	May requires coordination with additional agencies	*WSDOT Pilot*
	Harden roadway embankments/stream banks through placement of stone armor, gabions, retaining walls, etc.	Prevents increases in downstream flooding due to loss of flood storage upstream of culverts/bridges Relatively low capital cost	May require more significant maintenance needs than other options Increases velocity and shear stress conditions at the structures	*TEACR Roadway Surge ($)* *GC2 Highway Surge*

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Adaptation Category	Adaptation Strategy	Pros	Cons	Case Studies with More Information*
		Relatively short reconstruction time Offers a localized treatment technique to occur within DOT-owned ROW	May result in increased peak flow elevations upstream of a structure May not meet environmental requirements for a system (fish and aquatic organism passage)	
Relocate/raise roadway	Elevate the roadway or bridge above the projected flood elevations	Greatest likelihood of eliminating vulnerability	Very high capital cost May move flooding issues downstream	*IDOT Pilot* *TEACR Culvert ($)* *MnDOT Pilot ($)*

*($) indicates that cost information on the adaptation alternative is presented in the case study.

5.3.5. Riverine Flooding Knowledge Gaps

5.3.5.1. Precipitation Knowledge Gaps

Approaches are needed to simulate sub–24-hour projected precipitation data. Climate model data on precipitation are currently only recommended for use as a total volume over a 24-hour period. The use of sub–24-hour precipitation data are frequently necessary for proper modeling of peak stream flows from watersheds, particularly for smaller watersheds or for smaller return-period storm events.

Research on the creation of projected rainfall distribution type curves is needed. Current information from climate models on rainfall distribution patterns on an hourly or finer temporal scale is only qualitative in nature (e.g., a certain area may be projected to have more intense and flashier storm events) and does not provide the necessary details required for engineering analyses.

5.3.5.2. Flood Flow Knowledge Gaps

Research is needed on how to alter regional regression equations and stream gage studies to account for climate change. Regional regression equations and stream gage studies estimate flood flow values based upon statistical relationships measured in historical data. Neither approach currently includes methods for scaling of the equations to account for future climate conditions. However, FHWA and USGS are undertaking research on this topic. See Chapter 9 for more information.

5.3.5.3. Secondary Climate Impact Knowledge Gaps

Research and guidance is needed on the selection and evaluation of simultaneous weather events. Climate change is projected to increase or decrease the frequency of a wide range of weather events. The changes in likelihood of any individual event also alters the likelihood of simultaneous weather events (such as precipitation and wildfire or precipitation and coastal storm surge), which may result in much more severe damage to infrastructure. Research on the likelihood of overlap of these events is currently limited.

Research is needed on methods to project changes in land cover conditions, vegetation, and pests. Land cover is a directly controlling input variable in rainfall/runoff models that is commonly incorporated by practitioners based on current conditions. The impacts of climate change on the natural landscape due to potential changes in land cover, pest propagation, impacts on vegetative cover, and future development patterns are not well known but reasonably can be expected to change. Research into these topics can influence the land cover decisions made by practitioners in the development of rainfall/runoff models considering non-stationarity.

Additional model studies are needed on projected soil moisture conditions. Soil moisture conditions influence rainfall/runoff models through the initial interaction of precipitation with watershed soils. Research into relative shifts in soil moisture conditions under varied climate change scenarios using dynamic water budget models will aid hydrologic modelers in the development of rainfall/runoff models, without requiring them to invest significant resources into project-specific water budget modeling.

Research is needed on climate change impacts to river geomorphology. It is reasonable to expect that river geomorphology or general stability will shift under changing climate conditions. While general impacts can be anticipated based on past observations related to watershed development's role in river geomorphology, the timescale and severity of climate change impacts on stream geomorphology is currently unknown. However, FHWA is undertaking research on this topic. See Chapter 9 for more information.

Research is needed on accelerated glacial melt impacts to streams. Glacial melt is anticipated to accelerate under changing climate conditions. The influence of glacial melt on peak river flow rates, sediment transport processes, and general river geomorphology are generally unknown.

Additional future climate data are needed on annual snow coverage. If more precipitation falls as rain rather than snow in winter and spring, there is an increased risk of landslides, slope failures, and floods from the runoff (particularly from rain on snow events), causing road washouts and closures as well as the need for road repair and reconstruction. However, climate modelers currently do not recommend pairing climate model temperature and precipitation data to determine the form of precipitation.

5.3.5.4. Wildfire Impact on Hydrology Knowledge Gaps

Research is needed on the impacts of climate change on wildfire probability. A better understanding of the future probability of wildfire occurrence for a given area would add to the robustness of engineering studies and economic analyses (see Figure 22 of a roadway breach in a post-wildfire watershed). While there are potential models[51] for prediction of wildfire occurrence, the available models found in literature have prohibitively complex model inputs.

FIGURE 22: ROADWAY BREACHING AFTER FLOOD EVENT IN A POST-WILDFIRE WATERSHED, CALIFORNIA.

Photo credit: US Forest Service.

An improved correlation between existing land cover and post-fire soil burn severity is needed. Wildfire burn watershed models are generally dependent on mapping of the watershed's soil burn severity. Development of a predictive model for soil burn severity is a necessary step in the development

[51] Preidler et al., 2004.

of predictive design models that include wildfire burn. In the *TEACR Culvert* study, FHWA performed a cross-correlation between soil burn severity and wildfire intensity in an attempt to bridge this gap. However, the analysis was limited to a single data set with only regional applicability.

5.4. Pavement and Soils

This chapter describes some of the lessons learned from recent FHWA case studies regarding the effects of climate stressors on pavement, pavement subgrade, and slope and rock stability. Research is relatively nascent on the vulnerability of these assets to climate change hazards and resiliency approaches to reduce their vulnerability.

5.4.1. Pavement and Soils Sensitivities to Climate Change

The pavement system (i.e., pavement surface, base courses, subgrade, in situ, and constructed soils), and soil and rock slopes are vulnerable to changes in temperature, precipitation, and moisture, in the following ways:

- **Pavement**: Extreme temperatures may lead to increased pavement distress such as rutting and cracking in asphalt concrete (AC) pavements and there will be an increase in punchout[52] for continuously reinforced concrete pavement (CRCP) if temperatures exceed the design, placement, or performance thresholds (e.g., binder specifications for performance graded asphalt binders). Figure 23 shows a typical CRCP punchout.
- **Roadway subgrade and in situ soils**: Changes in the depth of frost penetration, freeze-thaw cycles, wet-dry cycles, and ground water table levels can affect the durability and engineering properties of pavement materials and subgrade shrink/swell properties (e.g., strength and deformation characteristics). In turn, these

FIGURE 23: TYPICAL CRCP PUNCHOUT.

Source: Texas DOT.

[52] Punchouts are localized slab failures characterized by closely spaced transverse cracks, often connected by short longitudinal crack(s) and joints.

changes can contribute to more rapid distress accumulation and smoothness deterioration of pavements (see Figure 24). Permafrost thaw will affect the engineering properties of soil supporting the roadway infrastructure. These changes to the supporting soils can result in significant travel-way and shoulder deformation and affect the performance of the roadway.

Figure 24: Pavement damage from expansive

Source: *TEACR Pavement Shrink-Swell* study.

- **Rock slopes**: Increased frequency of freeze-thaw and wet-dry cycles can accelerate rock slope weathering, which can destabilize the rock and result in rockfalls.
- **Soil slopes:** Precipitation levels affect soil moisture and groundwater conditions, which is a factor in the effective stress on soils that can, in turn, affect slope stability and result in landslides (see Figure 25).

5.4.2. Existing FHWA Guidance and Research on Climate Change, Pavements and Soils

In 2015, FHWA released a TechBrief on *Climate Change Adaptation for Pavements.*[53] Although the tech brief is not formal guidance, it does provide an overview of climate change and pavement-specific impacts, as well as potential adaptation strategies.

The findings and insights highlighted in this chapter come from the case studies in Table 13. The table includes hyperlinks to the complete case studies. For more information on any of these studies, please review the full case study reports.

Figure 25: Upper Escarpment Along Virginia I-77 from the *TEACR Slope Stability* study.

Source: Virginia Department of Transportation.

[53] FHWA, 2015a.

Table 13: Pavement and Soils Adaptation Case Studies[54]

Study Name	Location	Asset Type	Climate Change Stressor(s)
WFLHD/ADOT&PF Pilot	Dalton Highway Mile Post (MP) 9 to MP 11, Alaska	Roadway	Temperature, sea level rise, wind, landslides
GC2 Pavement	Alabama, statewide	Roadway pavement	Temperature
TEACR Pavement Shrink-Swell	State Highway 170, near Dallas, Texas	Roadway pavement	Precipitation, temperature
TEACR Slope Stability	I-77, MP 1.8 to MP 6.3, Carroll Co. Virginia	Rock slope, soil slope adjacent to highway	Precipitation, temperature
TEACR Pavement Freeze-Thaw	St. Rte. 6/ St. Rte. 15/ St. Rte. 16, Piscataquis County, Maine	Pavement	Precipitation, temperature

5.4.3. Lessons Learned from Studies of Pavement and Soils

The research teams for each of the case studies highlighted many lessons learned during study development. The following sections highlight some of the cross-cutting lessons regarding pavement and soils vulnerabilities and possible adaptation strategies to mitigate the effects of climate stressors. See Table 14 for a summary of the lessons learned.

The lessons in the Section 5.1 (Overarching Lessons Learned) are also highly relevant to pavement and soils and should be carefully reviewed.

Table 14: Lessons Learned from Pavement and Soils Engineering Adaptation Assessments

Lesson Category	Lessons Learned
Impacts on Pavement	Changes in temperature and precipitation could have widespread impacts on pavement performance, resulting in significant adaptation costs.
	Temperature and moisture changes affect the entire pavement system.
	Pavement designers must account for climate uncertainty when assessing existing pavement systems and developing pavement mix designs.
	Climate change will affect seasonal truckload restriction policies.

[54] Throughout this section, case studies are referred to by an abbreviated title. For a full list of the case studies referenced in this report and their complete titles (with hyperlinks), see Appendix A: List of Case Studies.

Lesson Category	Lessons Learned
	Although the current state of climate model data is not "plug-and-play" with current pavement design and analysis tools, practitioners can frequently develop workarounds.
Impacts on Landslides and Rock Falls	Detailed climate data are not necessary for an initial, general assessment of climate change impacts on soil stability.
	To determine if climate change will increase weathering, practitioners must consider projections of freeze-thaw cycle frequency, temperatures, and precipitation amount, as well as the relative timing of these events.
Impacts on Permafrost Thaw	Location-specific permafrost and soil data are critical.
	The warming associated with climate change may be too great to enable long-term prevention of permafrost thaw underneath a roadway.

5.4.3.1. Impacts on Pavement

Changes in temperature and precipitation could have widespread impacts on pavement, resulting in significant adaptation costs. Climate data projections indicate that temperature and precipitation changes will have systematic and long-term adverse consequences on the performance of pavements that warrant preservation action. Climate change is slow on the scale of current pavement lifecycles (e.g., 20-14 years) so (1) in most cases, immediate adaptation responses are not yet warranted, but (2) ultimately some adaptive efforts must occur.[55] The cost premium for upgrades in design specifications may be low at a project level; however, since the effects will be systemic and statewide, the budgetary implications of adopting enhancements at the agency level warrants consideration. The *TEACR Pavement Shrink-Swell* study discusses this issue in detail and provides an example.

Temperature and moisture changes affect the entire pavement system, both the surface layers and subgrade/soils. For example, FHWA studies conducted in Texas (*TEACR Pavement Shrink-Swell*) and Alabama (*GC2 Pavement*) showed that the projected climate changes in those locations would result in higher pavement temperatures, along with drier ambient and subgrade conditions. These conditions could lead to a modest increase in pavement distresses such as fatigue cracking and rutting for AC pavements, and punchout potential for continuously reinforced concrete (CRCP).

Pavement designers must account for climate uncertainty when assessing existing pavement systems and developing pavement mix designs. Designers should compare current default design values to projected values for moisture and temperature over the lifecycle of the existing or proposed pavement. If designers expect the climate projections to exceed the

[55] FHWA, 2015a.

default temperature and moisture values currently in use for pavement design earlier than it would be typically scheduled for rehabilitation, they should update the climate-related design values using the best climate data projections available.

Climate change will affect seasonal truckload restriction policies. Winter weight premiums allow heavier truck loads during times when the ground is frozen, since frozen ground provides more support to the pavement system, resulting in less pavement damage from the heavier loads. Shorter freezing seasons will lead to shorter and lighter allowances in winter weight premiums.[56] As a result, there will be fewer opportunities for DOTs and the trucking industry to take advantage of the lower damage potential of pavements under frozen conditions. Similarly, there will be a need for early posting of spring load restrictions to accommodate the early on-set of spring thaw.

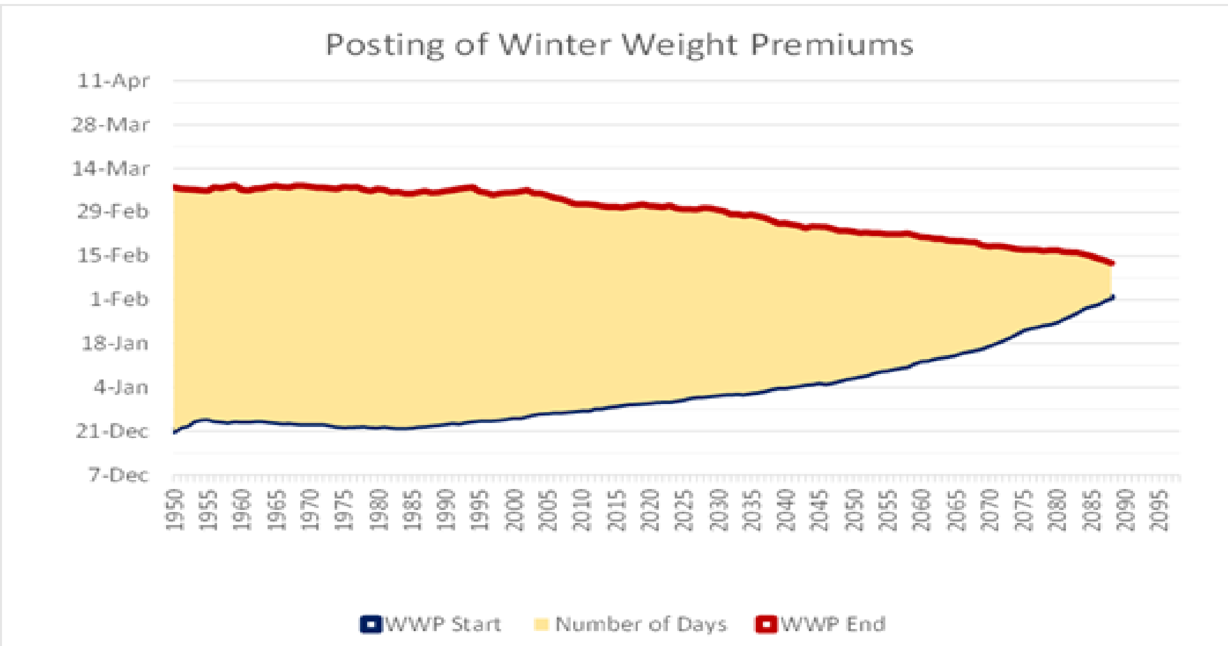

FIGURE 26: PLOT OF WINTER WEIGHT PREMIUM START AND END DATES.

Source: *TEACR Pavement Freeze-Thaw* study.

In the *TEACR Pavement Freeze-Thaw* study, the research team analyzed the impacts of temperature projections under RCP 8.5 on future seasonal load restriction policies. To help set seasonal load restriction policies, the analysis focused on when the freezing season would begin, the duration of the freezing, and when thawing would begin. Figure 26 shows the degree to which the duration of winter weight premiums decrease with the RCP 8.5 temperature projections. See the study for the detailed results.

56 The *TEACR Pavement Freeze-Thaw* study.

Although the current state of climate model projections is not "plug-and-play" with current pavement design and analysis tools, practitioners can frequently develop workarounds. In the TEACR case studies, FHWA used different workarounds for flexible and rigid pavements, as follows:

- **Flexible pavement (asphalt):** To develop the *TEACR Pavement Shrink-Swell* and the *TEACR Pavement Freeze-Thaw* studies, FHWA employed, primarily, the Asphalt Institute's models and, where necessary, used simplified versions of the AASHTOWare Pavement ME Design models. The primary drawback with the Asphalt Institute method is the lack of reliability considerations in pavement design analysis to address uncertainties relating to climate factors, traffic, properties of pavement materials and subgrade, and expected performance. In addition, while the AASHTOWare Pavement ME Design methodology is equipped to account for reliability considerations, the method requires hourly records of five different climate inputs: temperature, precipitation, wind speed, cloud cover or percent sunshine, and relative humidity. Climate models are not designed to provide hourly records at acceptable levels of data accuracy.
- **Rigid pavement (concrete):** In the *TEACR Pavement Shrink-Swell* study, FHWA used simplified versions of AASHTOWare Pavement ME Design analytical models to determine the percent change in CRCP design parameters for crack width and crack spacing, and punchouts. Recognizing its criticality, FHWA identified a workaround to develop future relative humidity values and used them in the CRCP design analysis, as this information is not readily available from climate models. FHWA used empirical models to develop estimates of future relative humidity based on temperature projections.

5.4.3.2. Impacts on Landslides and Rock Falls

Detailed climate data are not necessary for an initial, general assessment of climate change impacts on soil stability. The need for climate projections can be determined based on the results of an advanced parametric study (a sensitivity analysis). Practitioners can use a parametric analysis in place of climate projection data when initially examining variations in slope factor of safety[57] before drawing conclusions about the stressors' effects. If the parametric analysis indicates the potential for failure, then practitioners can conduct a detailed analysis of the slope's vulnerability to increased groundwater and precipitation levels using localized climate projection data and site-specific instrumentation. This approach may save

[57] Factor of safety in slope stability applications refers to the ratio of shear stress (the force caused by the sliding materials) to available shear strength along a failure plane. Values less than one indicate an unstable slope at high risk of failure. Permanent slopes are typically designed to a factor of safety of 1.5.

time and resources by providing insight on whether detailed data collection is necessary. For example, in the *TEACR Slope Stability* study, FHWA used a parametric study to assess the potential for a landslide by modeling changes in the slope factor of safety due to increases in groundwater and associated changes in the soil unit weight from increased future precipitation. FHWA concluded that a detailed study was not needed at this site because the magnitude of groundwater increase needed to significantly change the landslide potential was outside the realm of likely future climate changes.

To determine if climate change will increase weathering, practitioners must consider projections of freeze-thaw cycle frequency, temperatures, and precipitation amount, as well as the relative timing of these events. In the *TEACR Slope Stability* study, FHWA determined that only projecting the frequency of future freeze-thaw events[58] is insufficient to correctly predict the climate's effect on rockfalls triggered by excess fluid pressures or friction reduction in existing rock fractures. In addition, it is important to analyze the relationship between the timing and amount of precipitation, and projected temperatures, because freeze-thaw events that occur within a day or two of a precipitation event will have a more severe negative impact on the rock slope. Climate models can provide this information but, as with all climate projection data, users should think of it as "average" scenarios rather than outright predictions.

5.4.3.3. Permafrost Thaw

Location-specific permafrost and soil data are critical. In the Northern Hemisphere, continuous permafrost lies generally in Alaska and countries north of the 50th parallel.[59] Permafrost presence and ice richness along with soil type can vary greatly over short distances. Each of these factors play an important role in determining how much settlement will occur when permafrost thaws. As these factors vary, so too will the amount of settlement, leading to differential settlement over short distances. Variance in the amount of settlement over short distances is what causes damage to roadways; thus, understanding local soil and permafrost properties is crucial to accurately projecting future damage from permafrost thaw and for formulating effective adaptation options**.** Practitioners need to take a number of soil samples along their roadways to ensure that subsurface variability in permafrost and soil conditions is fully understood.[60]

The warming associated with climate change may be too great to enable full prevention of permafrost thaw underneath a roadway. In such situations, one goal of the adaptation

[58] The *TEACR Slope Stability* study defined freeze-thaw events as a day when the minimum temperature drops below freezing (32^{o} Fahrenheit, 0^{o} Celsius) and the maximum temperature is above freezing.
[59] International Permafrost Association, 1988.
[60] The *WFLHD/AKDOT&PF Pilot* study.

strategy should be to delay the thawing (and associated higher maintenance costs) for as long as possible. An enhanced maintenance regime should also be a critical component of the adaptation strategy in these cases.[61]

5.4.4. Adaptation Strategies for Pavements and Soils

For many of the case studies, the research teams developed adaptation strategies to address the projected impacts of climate change on the subject infrastructure. Table 15 provides a summary of the adaptation strategies considered by the research teams. Although the strategies developed are by no means exhaustive, they do represent the types of actions that practitioners could consider.

In addition to presenting potential adaptation options, Table 15 provides information on the benefits and drawbacks of the adaptation strategies, which may influence the selection of a particular strategy in a given location. The table groups the adaptation strategies to provide insight into the core types of actions that may be useful to increase resilience. The core types of actions are described below.

Core adaptation strategies for pavements include:

- **Adjust mix design**—Adjust pavement binder and mix design specifications to compensate for the expected increase in pavement distress due to higher temperatures and high intensity, short duration rain events.
- **Adjust the pavement structural design**—Adjust pavement structural design to compensate for the expected increase in pavement distress due to changing temperature and precipitation levels. Figure 27 shows an underdrain installation to drain the pavement base and subgrade.

FIGURE 27: UNDERDRAIN INSTALLATION.

Source: Ohio Department of Transportation.

- **Modify specifications**—Modify specifications to improve pavement quality characteristics and reduce variations. Modifications could include requiring reduced air voids in asphalt mixtures and more stringent tolerances for the mix.

Core adaptation strategies for soils include:

[61]The *TEACR Permafrost Thaw* study.

- **Stabilize the slopes**—Implement adaptation measures that hold the slope surface in place, such as managing surface water to reduce infiltration, establishing vegetation to protect the slope and reduce surface runoff, installing manufactured slope stabilization and erosion control products.

FIGURE 28: COMPLETED TOE WALL AT THE BASE OF THE SLIDING MASS AT I-77, MP 1.8 , VA I-77.

Source: Virginia Department of Transportation.

- **Install protective structures**—Install a physical structure to shield the asset downhill from the slope such as the toe wall constructed by VDOT in the *TEACR Slope Stability* study (see Figure 28).
- **Avoidance**—Plan the horizontal or vertical location of a roadway to avoid slide prone soils.

Core adaptation strategies for permafrost thaw include:

- **Prevent/delay thawing**—Prevent heat from affecting the permafrost by insulating the permafrost layer or drawing the heat from the soils above the layer.
- **Enhance maintenance**—In cases where permafrost thawing cannot be prevented, enhanced maintenance regimes will need to be instituted. Regular, near-constant maintenance will likely be necessary and increased funding allocations, equipment positioning, materials stockpiles, etc. should all be planned for.

TABLE 15: POTENTIAL ADAPTATION STRATEGIES INVESTIGATED IN THE PAVEMENT AND SOIL CASE STUDIES

Adaptation Category	Adaptation Strategy	Pros	Cons	Case Studies with More Information*
Adjust Mix Design	Adjust the asphalt binder grade based on future temperature projections Use higher percentages of crushed aggregates and manufactured fines to improve the aggregate interlock Decrease the binder content for pavement layers closer to the surface to control AC rutting while increasing the binder content for layers closer to the bottom Add lime to stiffen the mix	Compensates for the softening of asphalt concrete and decreases fatigue damage and rutting	Higher capital cost than conventional practices	*TEACR Pavement Shrink-Swell* ($)
Adjust the Pavement Structural Design	Increase steel content and use a stiffer binder in the asphalt overlay during rehab	Controls distress on concrete pavements and decreases crack width	Higher capital cost than conventional practices	*TEACR Pavement Shrink-Swell* ($)
	Modify the pavement and base course thickness and materials	Compensates for the softening of asphalt concrete layers and weaker subgrade	Higher capital cost than conventional practices	*TEACR Pavement Freeze-Thaw* ($)
	Improve subsurface drainage by cleaning underdrains, installing various geotextiles such as pavement edge drains	Reduces infiltration of moisture into the subgrade and prevents base erosion	Higher capital cost than conventional practices	*TEACR Pavement Shrink-Swell* *TEACR Pavement Freeze-Thaw*
Modify Specifica-tions	Modify specifications to "tighten" quality requirements	Reduces material variations and air voids in asphalt mixtures	Higher capital cost than conventional practices	*TEACR Pavement Shrink-Swell*
Stabilize the Slopes	Install subsurface drainage (horizontal drains)	Reduces excess pore water pressure, which reduces slope instability	Capital cost and O&M required	*WFLHD/ADOT&PF Pilot* ($)

Adaptation Category	Adaptation Strategy	Pros	Cons	Case Studies with More Information*
	Provide surface drainage	Reduces the amount of surface runoff infiltration, preventing or delaying soil slope failure	Capital cost and O&M required	*TEACR Slope Stability* *WFLHD/ADOT&PF Pilot*
	Revegetate slope with native plants	Reestablishes permanent ground cover	Capital cost and O&M required Provides marginal stabilization but does not prevent larger landslide events	*WFLHD/ADOT&PF Pilot* ($)
	Remove unstable material	Well-suited where small volumes of excavation are involved and where poor soils are encountered at shallow depths	May be costly to control the excavation[62] and may not be practical for larger landslides	*WFLHD/ADOT&PF Pilot*
	Install in situ reinforcement (e.g., geosynthetic reinforcement, soil nails, micropiles, plate pile)	Increases the resisting forces in a slope	Capital cost and O&M required	*WFLHD/ADOT&PF Pilot*

[62] The *WFLHD/ADOT&PF Pilot* study addresses a study slope in a national park, but this could apply to other sensitive areas as well. It states "Analysis is required to determine the extent of excavation needed to ensure stability. This adaptation option may selectively occur with ongoing observation and maintenance. This option would require earthmoving equipment to remove unstable materials and may result in the compromising of the character of the land, which is an important factor within a national park. Given the unknown extent of potentially unstable material in the study area, this option may not be feasible because of environmental impacts and wilderness boundary restrictions."

Adaptation Category	Adaptation Strategy	Pros	Cons	Case Studies with More Information*
Install Protective Structures	Construct retaining wall to protect road	Reduces the likelihood of a small landslide event affecting the road	Does not reduce the likelihood of a landslide event Larger landslide events may damage or destroy a retaining wall	*WFLHD/ADOT&PF Pilot* ($)
	Construct hardened, shed-type structure	Prevents landslide events from affecting road	Does not reduce the likelihood of a landslide event Large initial capital costs	*WFLHD/ADOT&PF Pilot* ($)
Adaptive Management	Before implementing a mitigation measure that addresses the worst-case scenario, implement the measure in steps to and monitor the results and continue to monitor the climate forecasts to determine if the next steps are warranted and, if so, when	Controls the impacts and costs of mitigation measures	The initial measure may be overdesigned if it is designed for the ultimate condition	*TEACR Slope Stability*
Avoidance	Move the roadway into stable hillside	Prevents landslide events from affecting road	May require extensive relocation of the roadway	*WFLHD/ADOT&PF Pilot*
	Move the roadway to the valley floor	Prevents landslide events from affecting road	Difficulties arise when the valley floor is a wetland, floodplain, and/or river channel	*WFLHD/ADOT&PF Pilot*

Adaptation Category	Adaptation Strategy	Pros	Cons	Case Studies with More Information*
	Construct a bridge over the landslide	Prevents landslide events from affecting road	Not appropriate for locations with there is uncertainty regarding exact location and volume of future potential sliding; high costs and environmental impacts	*WFLHD/ADOT&PF Pilot*
	Construct a tunnel	Prevents landslide events from affecting road	High costs and environmental impacts	*WFLHD/ADOT&PF Pilot*

*($) Indicates that there is cost information included in the cited study.

5.4.5. Pavement and Soils Knowledge Gaps

5.4.5.1. Pavement Knowledge Gaps

Practitioners need refined climate data and variables to use in existing pavement design models, or pavement design models need to be updated to use information that is available from existing climate models. To facilitate more precise estimation of pavement performance impacts using mechanistic-empirical design and analysis tools, future projections of critical climate variables (such as wind speed, cloud cover, and relative humidity) are needed at smaller temporal resolutions (ideally, hourly) with robust data quality. Currently, this is not possible. Alternatively, the models could be modified to work with the data available as was done in the *TEACR Pavement Shrink-Swell* study.

National temperature-based design maps need to be updated. As shown in the *TEACR Pavement Freeze-Thaw* study, the engineering tools to aid the selection of asphalt binder grade, FHWA's Long-Term Pavement Performance Bind (LTPPBind) 3.1 software, and its earlier version LTPPBind 2.1, use nationwide mapping of design temperatures based on *historical* weather data. Both the climate data and the design methodologies implemented in this tool need an update to incorporate projections of future climate data. This update would provide practitioners with the flexibility to work with a range of possibilities using both historical and forecasted data.

Practitioners need research on the economic impact of changing seasonal weight premiums and restrictions. As found in the *TEACR Pavement Freeze-Thaw* study, due to potential decreases in winter weight allowance periods, early postings for spring load restrictions, and increased pavement damage by trucks, there is a need to evaluate the impacts of changing seasonal load restriction policies on the trucking industry system-wide and to explore alternative strategies, such as repurposing freight networks, truck user fees, and pavement strengthening measures.

Practitioners need research on how warmer precipitation will influence soil properties. The *TEACR Pavement Freeze-Thaw* study assumed a recovery period of 120 days (i.e., the time required for subgrade to recover from "thaw" condition to "normal" unfrozen condition), which is solely a function of soil properties. However, practitioners must study further the validity of this recovery period to understand the influence of extended periods of soil saturation conditions due to increased or warmer types of precipitation (i.e., rain in lieu of snow) and the resulting shallower groundwater table.

Practitioners require more robust models to evaluate the impacts of intermittent drying and wetting cycles on pavement smoothness loss. The state-of-the-art pavement analytical models provide little insight on frost heaving or shrink-swell effects, while the existing models require validation and calibration with local experience. Changing climate factors will exacerbate this issue because the values used to calibrate the models to existing conditions and local experience will be no longer valid.

Practitioners need newer analytical models to understand the impacts of warming temperature on the thermal properties of bituminous mixtures, such as shrinkage cracking in asphalt pavement layers. Shrinkage cracking may occur when bituminous mixtures contract in response to loss of volatiles[63] or age-related hardening of asphalt binders. During the *TEACR Pavement Shrink-Swell* study, FHWA learned that, anecdotally, warmer temperature conditions in the future could cause this type of cracking to worsen. Thus, there is a need for models that can explain the materials' response to warmer temperatures over time, tests to optimize mix designs, and procedures to consider when designing both the mix and the pavement system structure. Since these models do not currently exist, FHWA was not able to determine the influence of long-term climate trends on future shrinkage cracking potential risks in bituminous layers in that case study.

Practitioners need analytical models to forecast changes in the groundwater table. These models would account for the interactions among climatic, site-specific, and hydrological characteristics.

5.4.5.2. Soils Knowledge Gaps

There is limited information on determining the effectiveness of geosynthetics for subgrade improvements in a changing climate. Figure 29 shows a variety of geosynthetics used in highway construction. While the benefits of using geosynthetics to improve the bearing capacity of subgrade are widely recognized, there is no nationally approved or validated analytical method for use in pavement design to quantify their contribution to pavement performance or quantifying their benefits. The National Cooperative Highway Research Program (NCHRP) has recognized this issue and is concluding a research project entitled "Quantifying the Influence of Geosynthetics on Pavement Performance" (NCHRP 01-50).

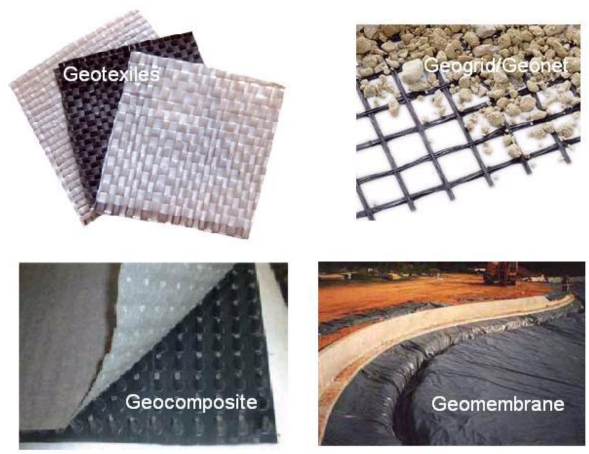

FIGURE 29: GEOSYNTHETICS USED IN HIGHWAY CONSTRUCTION.

Source: Grahams Child, English Language Wikipedia.

[63] Volatiles are petroleum compounds that are used in some asphalt mixes to make them more pliable.

There is limited information on how to tie precipitation events to ground movement for landslides. This gap exists today and needs to be filled to connect climate model data to increases or decreases in the frequency of local landslides.

There is a need to understand how changing vegetation types will affect slope stability. Currently, practitioners use vegetation to stabilize slopes, but the loss of vegetative cover and types of vegetation growing in a region may change as the climate shifts.

For studies of permafrost thaw, practitioners need more efficient techniques to account for mechanical deformation. Permafrost damage to a roadway often has two contributing components; thermal deformation and mechanical deformation. Thermal deformation considers only temperature's effect on permafrost thaw and roadway settlement. Mechanical deformation, on the other hand, considers the added contribution to settlement that the weight of vehicles on the road and the weight of the embankment itself can cause.[64] Modeling of these mechanical forces, important as they are, is presently a time-consuming exercise and, consequently, these forces are often not considered on typical design projects. As a warming environment hastens permafrost thaw, this becomes particularly important.

Permafrost mitigation knowledge is developing, but limited. As shown in the *TEACR Permafrost* study, there are adaptation strategies available at this time to mitigate permafrost thaw, but their effectiveness is still being studied. Additional research on the performance and effectiveness of various known approaches will help provide guidance to practitioners developing strategies to deal with permafrost thaw.

5.5. Mechanical and Electrical Systems

This chapter briefly describes mechanical and electrical systems, how they can be affected by climate change, lessons learned and possible adaptation strategies.

The range of equipment types and overarching systems that could be characterized as mechanical and electrical is quite broad. Transportation assets do not operate in isolation. They depend on a host of ancillary systems, without which there may be user delays or damage to transportation assets. For example, the electrical grid supplies necessary power to a wide range of

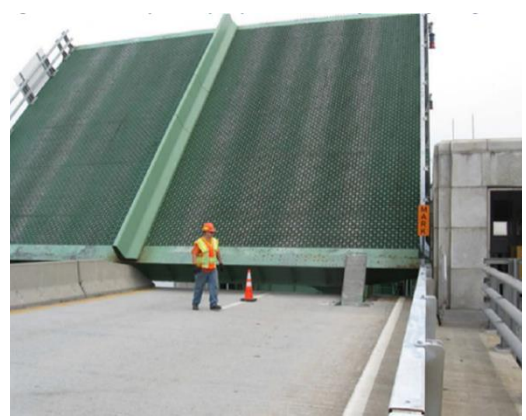

Figure 30: The Bascule Bridge on Loop Parkway over Long Creek.
Photo credit: FHWA.

[64] These factors may cause the water from thawed permafrost to get squeezed out laterally from underneath the roadway resulting in additional settlement beyond what thermal deformation alone produces. There may also be a tendency for the embankment to be pushed outwards as well as downwards because of all these forces.

transportation assets including mechanical components on moveable bridges, traffic signals, Intelligent Transportation Systems (ITS) (e.g., ramp meters, roadway sensors, variable message signs), and pumps that keep equipment and tunnels clear of water.

The assets considered in this chapter are limited to those addressed in recent studies, which primarily focus on bridge- and tunnel-related systems. These include various heating, ventilation, and air-conditioning (HVAC) equipment; switchgear; controls; sump pumps; fire pumps; tunnel exhaust fans; and moveable bridge mechanisms.

5.5.1. Mechanical and Electrical System Sensitivities to Climate Change

Several climate change stressors are typically relevant to mechanical and electrical systems, including flooding from sea level rise, storm surge, and increased precipitation; increased temperatures; and high winds. These sensitivities are described below in Table 16.

Table 16 lists the mechanical and electrical case studies that provided the findings and insights highlighted in this chapter, along with a brief description of the infrastructure assets and how they can be affected by the key climate stressors. Hyperlinks to the complete case studies are included in the table. For more information on any of these studies, please review the full case study reports. Figure 30 shows a typical bascule bridge.[65]

TABLE 16: MECHANICAL AND ELECTRICAL SYSTEM ADAPTATION CASE STUDIES[66]

Study Name	Climate Change Stressor(s)	Asset Type	Climate Impact Description
Sandy: Yellow Mill Drawbridge	• Sea level rise • Storm surge	Twin double-leaf bascule bridge mechanical pits and electrical rooms	Flooding can damage the machinery that moves the bridge spans and salt water can damage key electrical components.
Sandy: Loop Parkway Bridge	• Sea level rise • Storm surge • Extreme heat	Two-leaf bascule bridge mechanical and electrical systems	Salt water flooding the electrical equipment can short the circuits. Repeated salt water incursion can lead to corrosion. Mechanical systems subjected to very high temperatures can thermally expand and potentially increase friction between parts, causing mechanisms to lock up or otherwise fail. Extreme heat can lead to electrical equipment failure.

[65] A bascule bridge (sometimes referred to as a drawbridge) is a moveable bridge with a counterweight that continuously balances a span, or "leaf", throughout its upward swing to provide clearance for boat traffic.
[66] Throughout this section, case studies are referred to by an abbreviated title. For a full list of the case studies referenced in this report and their complete titles (with hyperlinks), see Appendix A: List of Case Studies.

Study Name	Climate Change Stressor(s)	Asset Type	Climate Impact Description
Sandy: Governor's Island Ventilation Building	• Sea level rise • Storm surge • Extreme precipitation	Ventilation building serving a tunnel	Flooding can short-circuit the electrical systems and corrode the mechanical equipment, causing the ventilation system to fail and disrupt service of the tunnel.
MassDOT Pilot	• Sea level rise • Storm surge	Tunnel and ancillary equipment including vent infrastructure, pump stations, and electrical substations	MassDOT considers all facility elements critical and subject to flooding above the original design flood elevation by 2070.
Sandy: Port Jersey Marine Terminal	• Sea level rise • Storm surge	Port terminal electrical equipment	Flooding can damage numerous circuit breakers in all three switchgear buildings. Equipment can be further damaged by corrosion.
GC2 Coal Terminal	• Sea level rise • Storm surge	Shipping pier	While the pier could withstand the impact of storm surge, all mechanical and electrical equipment atop the pier can be damaged from water overtopping the dock.

5.5.1.1. Mechanical and Electrical System Sensitivities to Flooding

Flooding may increase the likelihood of failure and increase maintenance requirements of electrical and mechanical equipment. Storm surge can flood operator houses and/or mechanical rooms (see Figure 31) causing the failure of normal and back-up power electrical systems and jamming gear mechanisms.[67]

Figure 31: Typical Electrical Panels Vulnerable to Water Damage.

Photo credit: WSP.

If junction boxes are inundated, the essential electrical equipment could short-circuit when back-up generators are activated. This is a concern for the Central Artery Tunnel Ventilation Building, shown

[67] The *Sandy: Loop Parkway Bridge* study.

in Figure 32, for example. Short-circuiting can result in extensive loss of service from any electrical equipment. Flooding with salt water can reduce the lifespan of the mechanical and electrical equipment. Corrosion impacts typically become more noticeable after repeated flooding events.

Existing pumps may be undersized for future water levels. Pumps that were initially installed to manage small water leaks are not designed for storm-based inundation; they will likely not be effective during inundation and may not survive inundation events. Equipment that has survived previous inundation events may not survive additional inundation episodes. For example, sump pumps installed at the Yellow Mill Drawbridge in Connecticut were insufficient to manage the inflow of water during Superstorm Sandy and Hurricane Irene.[68]

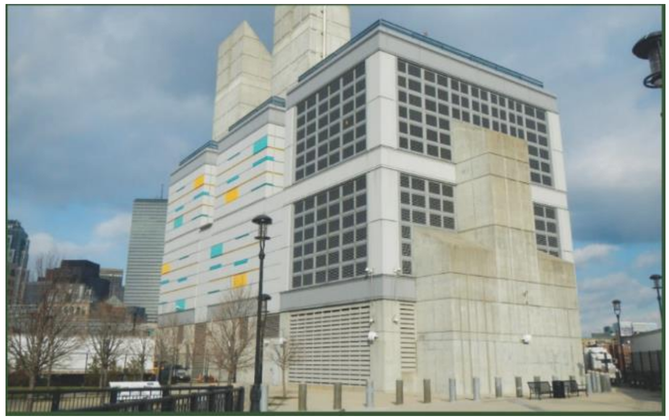

FIGURE 32: CENTRAL ARTERY TUNNEL VENTILATION BUILDING.

Source: *MassDOT Pilot* study.

5.5.1.2. Mechanical and Electrical System Sensitivities to Increased Temperatures

Increased temperatures during high heat events can affect mechanical and electrical equipment that is inadequately protected against overheating. These systems may temporarily go out of service or experience permanent damage. Extreme heat, particularly for sustained periods, may also affect the operation of moveable bridges due to thermal expansion, failure of electrical or mechanical equipment, and/or power outages.

5.5.1.3. Mechanical and Electrical System Sensitivities to High Winds

High winds can create uplift forces on structures and uproot mechanical equipment such as exhaust ducts, fans, air handling units, and other components located on the top of facilities. High winds can also affect large double doors. Practitioners can find further discussion and guidance in materials developed by FEMA.[69]

5.5.2. Lessons Learned from Studies on Mechanical and Electrical Systems

The research teams for each of the case studies highlighted many lessons learned. This section highlights some of the cross-cutting lessons regarding mechanical and electrical vulnerabilities and possible strategies to mitigate the effects of climate stressors. Table 17 groups and summarizes these cross-cutting lessons from the studies. Detailed information on each of the lessons, including examples from the individual studies follows the table.

[68] The *Sandy: Yellow Mill Drawbridge* study.
[69] FEMA 543, 2007.

Research into mechanical and electrical system vulnerabilities to these hazards and resiliency approaches to reduce vulnerability is relatively nascent. More research is needed before definitive guidance can be provided.

The lessons in the Section 5.1 (Overarching Lessons Learned) are also highly relevant to mechanical and electrical systems and should be carefully reviewed.

TABLE 17: LESSONS LEARNED FROM MECHANICAL AND ELECTRICAL SYSTEMS ENGINEERING ADAPTATION ASSESSMENTS

Lesson Category	Lesson Learned
Flooding	Water could enter mechanical and electrical rooms through many entry paths.
	Visuals of sea level rise and storm surge scenarios overlaid on as-built drawings can help communicate exposure.
Increased Temperatures	Key temperature thresholds can be selected using experience, professional judgment, and climate change scenarios.

5.5.2.1. Flooding

Water could enter mechanical and electrical rooms through many entry paths. The "weak link" in the system may not always be the most obvious entry path, such as overtopping tunnel approach walls.[70] Water can also enter through construction joints, utility conduits, duct banks, and un-grouted wall penetrations. Some equipment room openings are designed to prevent water entry from wave splashes or minor ponding, but are not watertight against hydrostatic pressure from a flood event.

Visuals of sea level rise and storm surge scenarios overlaid on as-built drawings can help communicate exposure. Conveying the impacts of weather events requires some level of stakeholder education. An effective way to communicate the exposure of mechanical and electrical components to flooding is by drawing lines that represent the elevation of the sea level rise and storm surge scenarios on an as-built drawing that includes the location of the equipment. For example, Figure 33 is an illustration from the *Sandy: Loop Parkway Bridge* study.

[70] *Sandy: Governor's Island Ventilation Building*

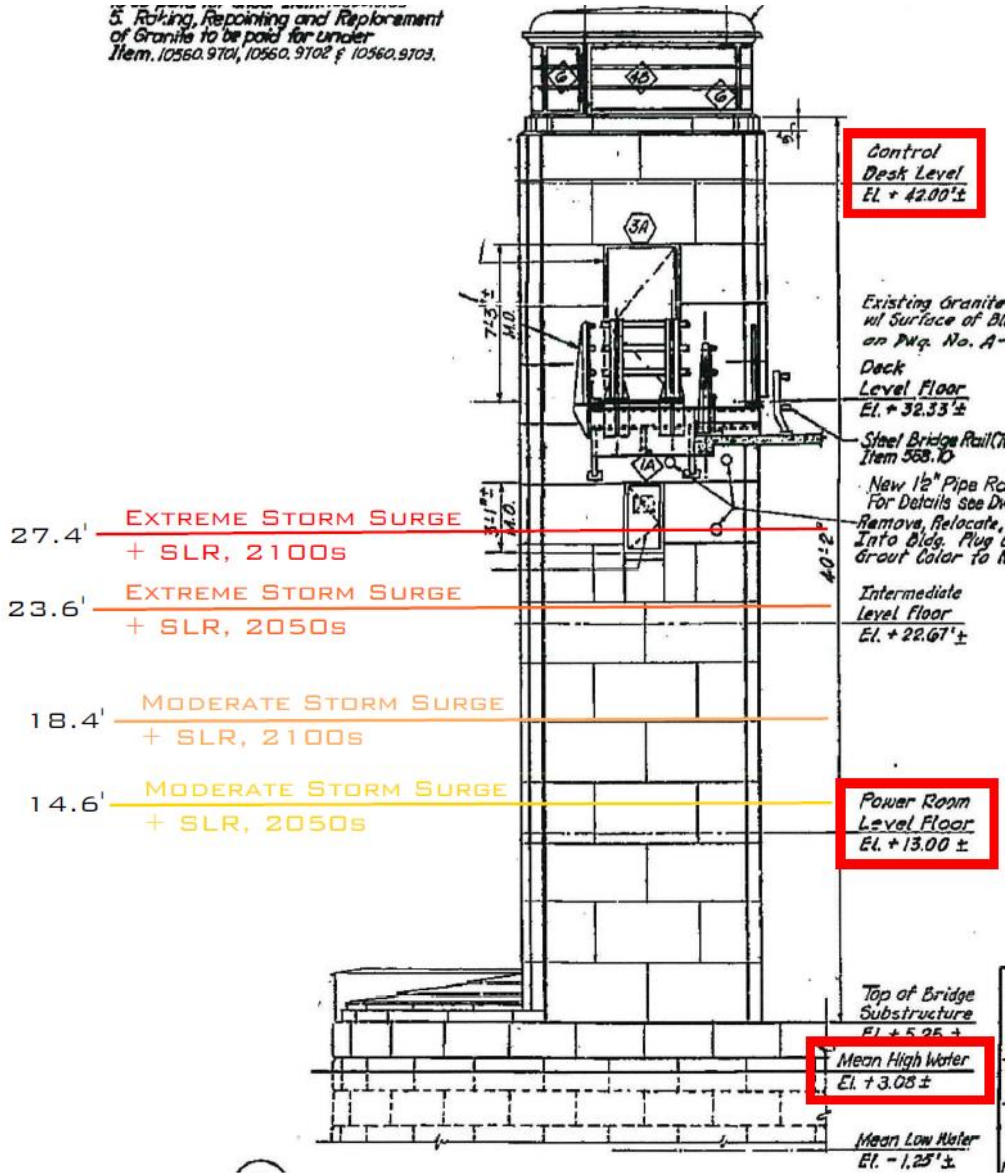

FIGURE 33: SANDY LOOP PARKWAY BRIDGE BASCULE PIER STRUCTURE ELEVATIONS RELATIVE TO WATER SURFACE ELEVATIONS.

Image Source: *Sandy: Loop Parkway Bridge*.

5.5.2.2. Increased Temperatures

Key temperature thresholds can be selected using experience, professional judgment, and climate change scenarios. In some locations, key thresholds, such as maximum permissible temperatures, may be documented. If not, thresholds can be developed using the professional judgment of local engineering and maintenance staff until further research is performed. In the *Sandy: Loop Parkway Bridge* assessment, the temperature thresholds of the bridge were selected based on the experience and professional judgment of the engineering team as they were not found in formal design guidelines. The team determined that single-day maximum temperatures and three-day average maximum temperatures that approach 110° Fahrenheit (43.3° Celsius) would result in an increased risk of the bascule bridge's mechanical components locking up because of thermal expansion. Once a threshold is determined, climate projection data can be used to estimate how much more frequently this threshold could be exceeded in the future.

5.5.3. Adaptation Strategies for Mechanical and Electrical Systems

Within the case studies reviewed for this chapter, the research teams developed adaptation strategies to address the projected impacts of climate change. Table 18 provides a summary of the adaptation strategies considered by the research teams. While this is by no means an exhaustive list of potential adaptation strategies, it does highlight some potential actions that could be considered in other locations.

In addition to presenting potential adaptation options, Table 18 also provides information on the benefits and drawbacks of various adaptation strategies that may influence the appropriateness of a particular strategy in a given location. In the table, the adaptation strategies are grouped to provide insight into the core types of actions that may be useful to increase resilience:

- **Dry Floodproof**— Designing or modifying a building, enclosure, or area to render it substantially impermeable to the entrance of floodwaters, thereby lowering the potential for flood damage. "Substantially impermeable" is usually defined as resulting in a maximum accumulation of 4 inches of water depth in a dry flood-proofed space during a 24 hour period.
- **Wet Floodproof**— Allows water to enter the structure/asset but limits or prevents damage to critical components.
- **Relocate Outside of the Projected Flood Area**— Such strategies include elevating the infrastructure or moving it to another location.
- **Minimize Operational Disruptions**—Install redundant or manual back-up systems to minimize disruptions if mechanical/electrical equipment is damaged.
- **Cool**— Increase air-conditioning capacity to keep the ambient temperature below the maximum operational temperature for the equipment. This may involve installing high volume air-conditioning equipment in electrical control rooms and transformer rooms above the design flood level.

Other sections (e.g., Coastal Hydraulics) may have additional adaptation strategies that could protect mechanical and electrical systems from climate impacts. For more information, refer to the specific case studies.

TABLE 18: POTENTIAL ADAPTATION STRATEGIES INVESTIGATED IN THE MECHANICAL/ELECTRICAL CASE STUDIES

Adaptation Category	Adaptation Strategy	Pros	Cons	Case Studies with More Information*
Dry Floodproof	Improve weatherproofing of mechanical and electrical rooms	Relatively inexpensive	Could complicate access for maintenance and operations	*Sandy: Loop Parkway Bridge ($)* *Sandy: Yellow Mill Drawbridge*
	Enhance sea walls (e.g., increase height, strengthen)	Can design so sea wall height can be increased in the future, as needed	Strictly structural solutions to storm surge protection can create collateral issues such as restricting physical access, requiring measures to control internal drainage, and various temporary and environmental impact	*Sandy: Governor's Island Ventilation Building ($)*
	Install flood gates	Effective at preventing tube flooding when properly maintained	Interrupts traffic access Not passable until approaches are pumped dry	*Sandy: Governor's Island Ventilation Building ($)*
Wet Floodproof	Elevate mechanical and electrical equipment, including back-up generators	Reduces probability of water damage and mitigates damage if it occurs	May be insufficient room to elevate in existing structures	*Sandy: Yellow Mill Drawbridge* *Sandy: Loop Parkway Bridge ($)*
	Increase pump capacity and install dedicated generators	Maintains access or reduces time that access is not possible	May not be practical for larger events	*Sandy: Governor's Island Ventilation Building ($)*
Relocate Outside of the Projected Flood Area	Replace bascule bridge with high-level span	Eliminates need for mechanical and electrical equipment More reliable access for land and marine vehicles	Expensive alternate to other strategies Potential for considerable environmental impacts Less flexibility in the clearance envelope	*Sandy: Yellow Mill Drawbridge*

Synthesis of Approaches for Addressing Resilience in Project Development

Adaptation Category	Adaptation Strategy	Pros	Cons	Case Studies with More Information*
Minimize Operational Disruptions	Install a manual hand crank to open bascule bridge as a back-up to electrical operation	Generally reliable Not reliant on electrical power	Only useful in an emergency Would take several hours to open the bridge	*Sandy: Loop Parkway Bridge*
	Install a back-up electric generation system	Ensures consistent power availability Can address outages from multiple climate impacts	Does not prevent damage to mechanical and electrical equipment during a storm surge Must ensure fuel availability, protect back-up generators	*Sandy: Loop Parkway Bridge ($)*
	Temporarily disconnect back-up generators to avoid short-circuiting the system	Prevents damage to the electrical system when water is present	Emergency power is not immediately available	*Sandy: Loop Parkway Bridge*
Cool	Install HVAC equipment in electrical room	Improves electrical equipment operation and longevity	Does not address grid-wide blackouts if the HVAC equipment is not also on auxiliary power	*Sandy: Loop Parkway Bridge ($)*

*($) Indicates that there is cost information included in the cited study.

5.5.4. Mechanical and Electrical Systems Knowledge Gaps

More research is needed into mechanical and electrical system vulnerabilities in order to develop more definitive guidance. Research to these hazards and resiliency approaches to reduce vulnerability is relatively nascent.

Standard thresholds for the temperature (single-day and multiday heat wave average) at which moveable bridges have an increased risk of failure are needed. In the *Loop Parkway Bridge* study, the research team relied on professional opinion because of the lack of available information.

A methodology for estimating the extent of disruption in the transportation network due to power failures is needed. Power redundancy is necessary to minimize the damages of power failures, and facilitate rapid restoration of transportation services. Methodologies are needed to determine what electric power investments—and specifically what investments in power redundancy—are necessary to maintain critical assets during extreme weather events and associated power outages.

More research is needed on the impacts of climate change to communications systems. Communications system are a vital component of a transportation system. They are particularly important following a major weather event, when they are critical for managing a response; loss of communication systems after a storm could delay repair and recovery efforts. To date, little research has been done regarding what increased risk climate change could pose to communication systems in the context of transportation operations. Information on the criticality of the communication system for the operation of the transportation network and the interconnectedness of these systems would inform investments in emergency communication networks and facilitate emergency response planning.

6. Conducting Economic Analyses

Economic analyses can assist public agencies in identifying and selecting the most efficient design and management alternatives, including a no-build option. Economic analyses provide insight into the comparative costs and benefits of alternatives and serve as the return-on-investment analysis for public agencies. They are valuable tools for agencies that inevitably face limited financial resources and must determine how to best allocate those resources across disparate needs in order to best meet their agency mission.

In the context of climate change adaptation measures, economic analyses quantify costs and benefits of different project options under each climate scenario. Economic analyses can help identify those options that are most efficient, inform the tradeoffs between adaptation options, and justify investments that enhance resilience. Economic analyses provide vital information on how cost-effective adaptation measures may be. However, selection of the most appropriate action would also ultimately take into account non-economic factors, including political feasibility, risk tolerance, and funding availability, as well as a number of social and environmental considerations (see Limitations of Economic Analyses box, below).

This chapter reflects a range of economic analysis techniques and lessons learned from the case studies referenced throughout this report. Economic analyses can range from simple to highly complex and the appropriate approach and cost estimation methods depend on resources available and the ultimate needs of the analyses, among other considerations.

Limitations of Economic Analyses

While economic analyses can help inform the adaptation decision-making process, they are just one of many considerations in the project development process. Some benefits of adaptation measures may not be captured within the determined scope of the economic analysis. Some benefits cannot be monetized and are not reflected in the analysis. Considerations beyond costs and benefits, such as the broader context of the agency and its strategy to address climate impacts, cannot be captured in economic analysis. For instance, an agency may decide to maintain flexibility in adaptation measures to pursue and adjust over time. See Chapter 7 on additional considerations provides information on other topics that should be factored into decision-making.

The chapter covers an overview of economic analyses of adaptation measures, considerations when determining the scope and complexity of such economic analyses, approaches to estimating costs and benefits of adaptation measures, and remaining knowledge gaps.

6.1. Overview of Economic Analysis of Adaptation Measures

Economic analyses monetize (i.e., put into dollar terms) the costs and benefits associated with measures over a specific analysis period so they can be compared. Thus in economic analyses as part of the traditional transportation project development process, the incremental cost of a measure, relative to the no-action scenario, is compared to the benefits it is anticipated to provide in order to determine if the measure is likely to be cost-efficient. Information on costs and benefits for each adaptation alternative helps practitioners identify the most efficient option to implement.

The following sections provide background on economic analyses, including an overview of economic metrics, key differences between traditional economic analyses and economic analyses for adaptation, and an overview of the case studies that included economic analyses of adaptation measures.

6.1.1. Overview of Economic Metrics

Economic metrics are derived at the end of economic analyses and are ultimately used to inform comparison of measures. Economic metrics include:

- **Benefit-cost ratio (BCR)** is a numeric ratio that expresses the discounted total benefits of the option relative to its discounted total costs (see Section 6.3.1 for details about discounting). If the BCR is above one, the project is considered cost-effective. When comparing adaptation options, the option with the highest BCR is the most cost-effective one.
- **Net present value (NPV)** is essentially the difference between the discounted total benefits of the option and the discounted total costs. If the NPV is greater than zero, the project is considered cost-effective and is expected to pay for itself over time. When comparing adaptation options, the option with the highest NPV is the most cost-effective one.

Each economic metric may provide different answers on the preferred measure, and it is useful to consider both if possible. For instance, NPV indicates the magnitude of the net benefits of an option while comparison of the BCR indicates the option that maximizes net benefit. As such, the BCR is frequently used to select among projects when funding restrictions apply. The economic metric selected will be consistent in revealing whether or not a strategy is cost-effective, but may rank the preferred measures differently. Several case studies evaluated both BCR and NPV, particularly if the BCRs between alternative scenarios are similar in magnitude, to provide a complete picture for decision-making.

Where a full economic analysis is outside the scope, initial analyses may result in these outputs, which can also be considered economic metrics:

- **Total costs** are the costs to build and maintain the design option plus the expected damage and socioeconomic costs over the asset's lifespan (see Section 6.3.2 Costs Overview). When comparing multiple design options, the best performing option is the one with lowest total cost.
- **Benefits** of adaptation measures evaluate the avoided costs of climate change impacts (see Section 6.3.3 Benefits Overview). Analysis of the benefits only may help provide an economic justification for the need for adaptation measures.

Since the estimated costs and benefits significantly affect the BCR and NPV, the bulk of this chapter details methods used to compute the inputs needed to calculate these metrics.

6.1.2. Key Differences between Traditional Economic Analyses and Adaptation Economic Analyses

Economic analyses performed to identify efficient adaptation options in the case studies presented in this chapter can be considered enhancements of traditional LCCAs, one of the three different types of traditional economic analyses that are used on transportation projects (see Overview of Traditional Economic Analyses for Transportation Projects box, below). However, there are some key differences in how LCCAs are applied to transportation adaptation projects when compared to traditional LCCAs.

Overview of Traditional Economic Analyses for Transportation Projects

Economic analyses play an important role in transportation decision-making. Different types of economic analyses are used as part of the traditional transportation project development process:

- **Benefit-cost analysis (BCA):** Comparison of the benefits to be generated by the project (e.g., congestion relief, safety improvements) relative to its capital costs. This type of analysis can be used in the project scoping phase to help an agency decide which projects are the most cost-efficient to pursue and the timing of implementation.
- **Lifecycle cost analysis (LCCA):** Comparison of the lifecycle costs of different design alternatives. Lifecycle costs consist of initial capital outlays plus long-term management costs, including material and labor costs as well as traffic disruption costs. LCCA is used to determine which design option has the lowest cost over a specific time horizon or analysis period (assuming each option provides the same user benefit); the option with the lowest initial capital cost may not have the lowest long-term costs. The climate risk-enhanced economic analyses conducted in the case studies presented in this chapter were LCCAs.
- **Economic impact analysis (EIA):** Quantifies economic development benefits of a project (e.g., number of jobs the project will create, urban development the project will stimulate). An EIA can be used in the scoping phase to help an agency justify a project. EIAs also play a role in supporting analysis of a project's broader economic impacts under the provisions of the National Environmental Policy Act (NEPA) for use of Federal-aid funding.

FHWA, the American Association of State Highway and Transportation Officials, the Transportation Research Board (TRB), and the academic community have promoted standardized practices for conducting economic analyses on transportation projects. Refer to FHWA's *Economic Analysis Primer* for additional information on traditional economic analyses on transportation projects. Incorporating climate change considerations into economic analyses of project options will introduce new complexities, however, which are not addressed in previously standardized practices.

For example, LCCAs in transportation projects have not traditionally considered damage repair and socioeconomic costs due to extreme weather events and climate change (e.g., increased travel delay costs, disruptions to the regional economy). Not including these climate-related costs may underestimate the benefits of avoided climate change-related impacts. Therefore, the analyses conducted by the case studies evaluated for this report included such costs in order to provide a more complete accounting of the benefits of the adaptation measures. Not including the costs of extreme weather events and climate change could underestimate the benefits of adaptation measures in the long term.

Additionally, economic analyses of adaptation alternatives may incorporate uncertainties or risks inherent in the assumptions of the future climate scenarios. An analysis that includes ranges for input variables to address uncertainties is often called a probabilistic analysis. Practitioners can use the distribution of probable outcomes from a probabilistic analysis as information to 1) decide whether the long-term benefits are positive and justify the implementation of an adaptation option considering its costs, and 2) identify the appropriate timing to implement the alternative scenario.

6.1.3. Overview of Case Studies Referenced in This Chapter

Table 19 provides an overview of the economic analyses used in various case studies. Indirect benefits and approach to event probabilities and damages, summarized in the table for each case study, are described in detail in Sections 6.3.3.3 Estimating Indirect Benefits and 6.3.4.2 Linking Event Probabilities and Damages, respectively.

TABLE 19: ECONOMIC ANALYSES IN CASE STUDIES[71]

Study Name	Type of Economic Metric	Approach to Event Probabilities and Damages	Include Indirect Benefits?
Full Economic Analyses			
TEACR Culvert	NPV, BCR	Hybrid Monte Carlo and Scenarios	Yes
TEACR Economic Assessments	Total Cost	Area Under the Curve, Monte Carlo	No
MaineDOT Pilot	NPV	Scenarios	No
GC2 Culvert	BCR, NPV	Monte Carlo	Yes
WFLHD/AKDOT&PF Pilot	BCR, NPV	Scenarios, Monte Carlo	No
MnDOT Pilot	BCR, NPV	Area Under the Curve	No
ODOT Pilot	BCR, NPV	Scenarios	Yes
Partial Economic Analyses			
TEACR Roadway Surge	Costs	Scenarios	No
TEACR Coastal Bridge	Benefits	Scenarios	Yes
Hillsborough MPO Pilot	Benefits	Scenarios	Yes
NYSDOT Pilot	Benefits	Scenarios	Yes

[71] Throughout this section, case studies are referred to by an abbreviated title. For a full list of the case studies referenced in this report and their complete titles (with hyperlinks), see Appendix A: List of Case Studies.

While the case studies provide illustrative examples of economic analyses of adaptation, agencies should take caution in generalizing the results of an economic analysis since cost and benefit estimates of adaptation measures vary by asset and location. It is rarely appropriate to transfer benefit valuation study information or results from one geography to another. Every location and asset is unique and therefore requires its own benefits valuation. For example, the *MaineDOT Pilot* study team found that in one town, the most cost-effective adaptation measure is to replace a bridge in-kind, while in the next town over, the most cost-effective solution is to replace the bridge with a significantly longer span due to differences in climate stressor-damage relationships and structural details regarding the range of candidate alternative designs.

6.2. Determining Scope and Complexity

As with traditional economic analyses, careful consideration needs to be given to the bounds of the analysis and assumptions because the results and how they are interpreted are greatly influenced by the analysis setup. The appropriate scope and complexity of an economic analysis of an adaptation measure may depend on the following factors:

- **Resources available.** Economic analyses may be demanding, in terms of time, data, and expertise. Some economic analysis approaches are more resource intensive than others and the approach practitioners decide on may depend on the amount of resources available.
- **Relative cost of implementing the adaptation measures(s).** If the adaptation measure is inexpensive, it may not make sense to do a detailed economic analysis. If the adaptation measure involves a significant investment, a detailed analysis may be warranted to help select the most appropriate course of action.
- **Cost of the facility.** Generally speaking, analysis of lower cost facilities may entail greater use of assumptions regarding various economic parameters under future climate conditions, whereas more expensive facilities may warrant better estimates. For higher cost facilities, more money is at stake, so it may be worth a higher investment in the economic analysis to make sure the most appropriate adaptation measure is selected.
- **Consideration of the broader system.** An economic analysis with a wide scope that includes the broader system may be informative about the economic impact of the adaptation measure on the network. A large project will likely have impacts on the broader system. In some cases, discrete decisions across a network may have a greater effect than a decision pertaining to one big project. For example, decisions at lower cost facilities repeated throughout a network can have a large impact.
- **Risk tolerance.** If an agency has low risk tolerance for failure of an asset, adaptation measures should be put in place regardless of the costs. Economic analyses should still be conducted to select the most cost-effective alternative. Additionally, an agency's risk

tolerance can also relate to overinvesting. If there is low risk tolerance for potentially overinvesting, then it may make sense to do a more detailed economic analysis.

- **Timeframe**. It is best to conduct the analysis to cover the expected service life of the asset in order to enable a full LCCA and fully capture the costs and benefits of the design alternatives under a long-time change in climate. A longer analysis period is preferred, especially for adaptation measures with large upfront costs and benefits that may not actualize for many years. It is also important to consider consistent analysis periods between multiple adaptation measures for a comparative analysis.
- **Geographic scope**. It is important to consider the appropriate geographic bounds for the economic analysis. For instance, while economic activity in an area with a road closure due to climate impacts may be stifled, activity may increase in neighboring communities. Consider whether the neighboring communities would be included in the analysis.

As resources allow, the broader system should be considered within the scope of the economic analysis, to account for the fact that more than one asset or site is likely to be impacted in a given climate event. For economic analyses that do not have the resources for a broader study, qualitative analysis of additional economic considerations may be appropriate (see Chapter 7). A corridor approach may be preferred since the availability of detour routes can be a key factor in determining outcomes of the economic analysis. Additionally, the cost efficiencies of developing an adaptation project at a larger scale may also influence the economic analysis outcomes toward more cost-effective results. For example, in the *ODOT Pilot* study, ODOT found that existence of viable detour routes for a single site was a key factor in determining outcomes of the economic analysis since available detours meant minimal impacts and, therefore, minimal benefits of adaptation options. A corridor-scale economic analysis would need to take into account larger failed sections of roadway if more than one site is likely to be impacted in a given event.

Different adaptation measures may be preferred depending on the scope of the analysis, such as whether or not costs associated with impacts beyond the ROW are included in the analysis. The magnitude of climate impacts to the surroundings may be contingent on the resilience of an asset. Including impacts and costs beyond highway rights-of-way, such as socioeconomic effects and land use impacts, bolsters the case for resilience actions. In the *GC2 Culvert* study, FHWA tested the sensitivity of the economic analysis to the inclusion of private property damage costs to nearby buildings from flooding attributable to the culvert. Particularly in an urban setting, flooding damage costs to adjacent high-value private property may be significant when compared to the repair/replacement cost of the structure itself. FHWA found that the BCRs were greatly enhanced due to the benefits of avoidable damage costs to properties.

6.3. Estimating Costs and Benefits

Although there are several methods of varying complexity available to conduct an economic analysis, all methods require estimating the costs and the benefits of measures. This section provides background on the importance of the discount rate selection and describes the types of costs and benefits that can be included in the economic analyses. For adaptation measures, climate change stressors and associated damages to the asset are key determinants of their benefits.

6.3.1. Selecting a Discount Rate

First, it is important to understand discounting of costs and benefits, a fundamental economic concept. The **discount rate** is a key input into an economic analysis. Discount rates account for the time-value of money. Discounting accounts for the fact that a dollar today is worth more than a dollar tomorrow, since today's dollar can be invested now and may yield a value greater than the initial dollar. Costs and benefits are discounted to reflect this fact and arrive at a **present value**. See FHWA's *Economic Analysis Primer* for additional background information on discount rates.

The selection of the discount rate will greatly impact the dollar value of the discounted cumulative expected costs associated with climate impacts. Although the relative results remain consistent regardless of the rate chosen, the dollar values of the benefits generally decline with a higher discount rate. That is, a higher discount rate places less value on a future dollar than a lower discount rate would.

It is worth conducting sensitivity testing around the discount rate to determine how it changes the results. For example, in the *TEACR Economic Assessments* study, FHWA tested the sensitivity of the economic analysis findings to multiple discount rates: no discounting, 1.4 percent, 3 percent, 3.5 percent, and 7 percent. Results indicate that economic analyses for climate adaptation projects are highly sensitive to the discount rate chosen; the analysis found large differences in the cumulative expected damage costs depending on which discount rate was used, and the discount rate could cause a project alternative to switch from having a positive NPV to a negative one.

6.3.2. Costs Overview

In economic analyses of climate adaptation measures, costs are generally the incremental lifecycle cost of implementing the adaptation measure, relative to the no-adaptation option baseline. Costs typically considered in LCCAs include both costs to the agency and "user costs," costs that travelers would incur rather than the agency.

Typical upfront cost considerations include:

- Increased upfront engineering, land acquisition, and construction costs.
- Increased travel delay costs, safety costs, and vehicle operating costs (e.g., higher vehicle fuel costs due to construction delays) during initial construction.

Ongoing costs include:

- Increased routine operation and general management costs, including increased travel delay, safety, and vehicle operating costs during management activities.
- Increased reconstruction or rehabilitation costs, including higher associated travel delay, safety, and vehicle operating costs.

Traditional techniques should be used in developing cost estimates for adaptation measures (see the FHWA's *Economic Analysis Primer* for additional guidance). Usually, cost estimates can be easily developed for adaptation measures since most measures comprise standard materials and construction approaches. As with traditional cost comparisons, the quantification of costs of adaptation measures should focus only on those costs that vary among alternatives.

For example, when considering capital costs for the replacement of culvert structures, the *NYSDOT Pilot* study research team concluded that there was not much difference in the size and cost of culverts needed for climate change and of those needed to meet another regional requirement. The cost of an increased barrel size was minor relative to the cost of traffic management and excavation during construction and furthermore, the cost of traffic management and excavation do not vary much at all based on the size of the culvert that is being installed. As such, the capital cost of culverts is a small part of the total lifecycle costs and therefore adaptation options resulting in upsizing recommendations during project design will frequently be economically justifiable.

Table 20 provides a summary of the costs and benefits considered in the case studies. Although each case study approached these concepts slightly differently, this table shows the main themes or common ideas used in determining the costs and benefits of adaptation measures.

Table 20: Costs and Benefits of Adaptation Measures

Costs of Adaptation Measures (Costs Incurred Relative to No-Adaptation Option)	Benefits of Adaptation (Costs Avoided Relative to No-Adaptation Option)
Costs to Agency: • Increased upfront engineering, land acquisition, and construction costs • Increased routine operation and general management costs • Increased reconstruction/rehabilitation costs ***Costs to Users:*** • Increased travel delay, safety, and vehicle operating costs during initial construction, maintenance activities, and reconstruction/rehabilitation	***Direct Benefits to Agency:*** • Reduction in physical damages, repair costs • Reduction in operations and management ***Direct Benefits to Primary Users:*** • Reduction in travel time costs from detours • Reduction in vehicle operating costs from detours • Reduction in disruptions to freight movement • Minimized cost of potential injury ***Indirect Benefits to Non-Primary Users:*** • Impacts of lost access to businesses and government fees/taxes on revenues • Impacts to nearby properties (e.g., flooding caused by an undersized culvert)

6.3.3. Benefits Overview

Depending on the nature of the adaptation project, a benefit can be thought of as any avoided future cost of climate change impacts. In addition, the benefits of adaptation may extend beyond avoided costs to include added value to the community or habitats enjoying the protected asset. Examples of benefits of adaptation may include:

- Reduction in the cost of repairs expected during the asset's lifetime as a result of becoming less susceptible to damage from extreme weather events.
- Reduction in user costs from having a more resilient asset.
- Reduction in regional economic losses to local businesses after damage from climate events has been incurred and during repairs.

When assessing the economics of climate adaptation options, determining what constitutes a benefit can be complex. The benefits may depend on what is included in the bounds of the analysis, relationship between the climate stressor and associated damages, and the magnitude and timing of the climate event. Often, quantitative analysis of benefits of adaptation measures take into consideration the incremental benefits of various adaptation measures compared to the no-build scenario and the tradeoffs associated with each scenario.

This section provides details about the types of benefits of adaptation measures.

6.3.3.1. Types of Benefits

Because benefits of adaptation measures can be diverse in nature, it is valuable to use common terminology to discuss types of benefits and their relative impacts. Economic analyses typically report benefits as two types of avoided costs: direct and indirect. Thinking about economic impacts in terms of these two categories of avoided costs can help decision-makers and stakeholders understand the scope and magnitude of the relevant benefits.

- **Direct** cost impacts of climate change are incurred by the agency and asset's primary users. Direct costs to the agency include management and repair of the asset. Direct costs to the users include disruption when the asset is not usable. For example, if a major highway floods and detour options are limited, drivers who rely on the highway would experience costs such as lost time and lost money (e.g., if a driver was unable to attend work due to the road closure). Direct benefits are associated with a reduction in repair costs for the agency, saving money for the asset's owners, or saving taxpayers' dollars in the short-term and the long-term. Direct impacts also include a reduction in disruption to primary users of an asset. When adaptation projects protect the highway from flooding, there is a direct benefit to the asset owner and to future drivers who will be less likely to experience direct costs. Therefore, it is worthwhile for a practitioner to evaluate direct costs of climate impacts to both the agency and primary users.

- **Indirect** cost impacts are incurred by entities who are not direct users of the asset, but would be affected by climate impacts to the asset. For example, if a road closure due to a climate event decreases the flow of traffic into a downtown business district and sales decline, store owners would bear an indirect cost. Similarly, indirect impacts take into account impacts on the broader economy, such as the reduction in disruptions to the regional economy. Continuing the previous example, business owners would experience an indirect impact if the road stays open and more customers have access to their goods and services, which triggers spending across their supply chain in related businesses as well as spending by their workers (often referred to as induced impacts).

A key consideration in determining the scope of an economic analysis, even for traditional transportation projects, is whether to include solely direct benefits or both direct and indirect benefits.

6.3.3.2. Estimating Direct Benefits

Since direct benefits are defined as avoided damages or disruptions to direct users, the calculation of the benefits is more complex than estimating the project cost. It involves considerations of the relationship between the climate stressor in question and the damage it could cause (see Section 6.3.4.1 Climate Stressor-Damage Relationship Curves for more detail), as well as considerations of the changing future likelihood and potential timing of damage (see Section 6.3.4.2 Techniques for Linking Event Probabilities and Damage for more detail). Risk, which can be defined as likelihood multiplied by potential damage, must also be taken into account.

Several studies quantified the benefits of avoiding extreme events as part of the assessment of asset performance. For instance, repair costs can be estimated by considering the costs of typical rehabilitation and replacement work items as well as applying upward adjustments, where appropriate, to account for higher mobilization costs in unexpected emergency situations. To calculate costs of impacts to the users, *MnDOT Pilot* study used the state DOT's recommended operating costs, travel time values for motorists and freight, and costs of crashes. Additionally, experience during historical events can help estimate duration of disruption and recovery time.

Traveler impacts can be estimated using a travel demand model or, more simply, by identifying the most likely detour route using web-based mapping software, assuming all travelers use that route, and calculating the additional distance traveled. This approach is not as resource intensive as using a travel demand model but provides less robust results.

6.3.3.3. Estimating Indirect Benefits

One approach to estimating indirect benefits is to apply regional economic models, which enable users to estimate economic losses from reduced trips and delays due to climate impacts within a specified study region. Economic models also allow users to determine the regional economic impacts of adaptation expenditures versus no-action scenario expenditures. The reduction in economic costs when an adaptation measure is implemented, as compared to no-adaptation measure, can be considered the indirect regional benefits.

For example, in the *TEACR Coastal Bridge* study, FHWA used the economic impact modeling software IMPLAN to estimate the climate-related economic impacts, including indirect impacts, of a potential bridge closure on the Mobile, Alabama, regional economy. IMPLAN allows users to model spending or demand changes in specific industries to determine the economy-wide employment, labor income, gross state product, industry activity, and tax impact associated with the initial spending. In this case study, the direct costs analyzed included costs associated with a disruption in the use of the bridge on the bridge's primary users, such as additional travel time incurred by passenger vehicles, the additional operation and management costs incurred by passenger vehicles, and the operation and management costs incurred by freight vehicles. The indirect costs analyzed were costs experienced by the downtown businesses that would lose customers if bridge access were disrupted, making it difficult for the customers to access those businesses. The indirect costs were driven by the fact that increased passenger time and travel costs likely impact personal travel and purchase decisions. These decisions in turn could have a negative impact on economic activity in downtown Mobile, the geography immediately adjacent to the bridge. State and local governments would also experience loss in potential tax revenue because of a bridge disruption; fewer trips into the city and less spending translate into untapped tax revenue within the project area.

For a more robust assessment, practitioners can remove the links associated with the study asset within a travel demand model to quantify the impact of loss on travel more precisely. For example, Hillsborough MPO in the *Hillsborough MPO Pilot* study used its regional travel demand model, the Tampa Bay Regional Planning Model, to evaluate the impacts of roadway link closures due to flooding, including delays and lost trips. The results were then input into the regional planning commission's Regional Economic Models Inc. (REMI) model to assess potential state and regional economic impacts including changes in operating costs, work hours, income, and gross regional product.

Quantifying the regional impacts of losing an asset can add more detail to an economic analysis for critical assets and can help practitioners understand the potential value of investing in adaptation measures. This analysis can be done on its own or it can be folded back into the climate stressor-damage relationship curve (see Section 6.3.4.1 Climate Stressor-Damage Relationship Curves) to refine the relationship between weather events and damages.

However, the scope of the regional system and users that may be affected by indirect impacts greatly influences the results of the analysis. For example, Hillsborough MPO found that three of five adaptation measures evaluated were not cost-effective. These results may have been due to overly conservative assumptions in modeling regional mobility losses in which only the facility in question is removed from the travel demand model, leaving adjacent and connecting links unaffected. In reality, it is likely that the other links would also be affected.

6.3.4. Estimating Cumulative Benefits under a Changing Climate

Estimating cumulative benefits of adaptation measures for an LCCA is more complex than traditional techniques because avoided costs will depend on changes in climate over time. Calculating benefits often takes the difference in total lifecycle costs between the base case design and the adaptation option (i.e., benefits = total base case lifecycle costs—total adaptation option lifecycle costs) and counts the avoided costs as benefits. Cumulative weather-related costs likely to be incurred by an asset over its lifespan are “lifecycle weather-related costs.” Adding the expected lifecycle weather costs to other routine costs (from operations, inspections, standard management actions, etc.) results in “total lifecycle costs.”

This section covers development of curves to estimate the relationship between climate stressors and associated damages, and various techniques for linking climate event probabilities and damage.

Techniques to calculate cumulative benefits differ depending on whether the impacts from the climate stressor(s) are chronic or acute. Chronic climate stressors, such as gradual increases in temperature, are slow and change over time. Acute climate stressors are short-lived, sporadic events such as flood or storm events. This section does not cover chronic stressors, as the case studies did not conduct economic analyses for chronic stressors (see box, Calculating Benefits for Chronic Stressors).

Calculating Benefits for Chronic Stressors

Chronic climate stressors must be handled differently than acute climate stressors when conducting climate-risk enhanced economic analyses. Unlike acute stressors, which cause immediate damage during distinct short-lived events like storms, chronic climate stressors involve slow changes to climate variables that, over time, can lead to premature asset deterioration. The additional costs attributable to chronic climate stressors are best determined by calculating the incremental maintenance and rehabilitation costs incurred by a design option under different climate scenarios. Assigning costs to maintenance/rehabilitation activities is a standard part of traditional lifecycle cost analyses. The new element that climate change adds is determining how much more frequently and/or intensively these activities will need to take place in the future. Making this determination will require close cooperation with engineers and asset management professionals who can provide insights on changes to asset deterioration rates under different climate conditions. Once new maintenance/rehabilitation regimes have been determined, standard lifecycle cost analysis procedures can be used to discount and sum the costs to arrive at an estimated total lifecycle cost for each design option under each climate scenario. Benefits can then be determined by calculating the savings in total lifecycle costs provided by the adaptation option relative to the base case design. The value of the benefit can then be carried forward and used to develop BCRs or NPVs so that the most cost-effective adaptation option can be identified.

6.3.4.1. Climate Stressor-Damage Relationship Curves

Direct and indirect weather-related costs vary depending on the severity/intensity of climate stressors. In most cases (but not all), the more severe the weather event, the higher the associated costs. The relationship between the intensity of a climate stressor and the associated costs can be captured in a line graph known as a climate stressor-damage relationship curve. A climate stressor-damage relationship curve brings together the engineering knowledge of the physical damage likely to be caused by a climate stressor, the engineering cost estimates to repair the damage, and (if desired) the costs to the user and the broader economy from any disruption. These curves are critical inputs to Monte Carlo analyses or other calculation techniques (described in Section 6.3.4.2 Techniques for Linking Event Probabilities and Damage) that aim to estimate lifecycle damage costs for the asset.

It is easiest to understand the concept of climate stressor-damage curves through an example. Figure 34 shows example curves for a roadway stream crossing from the *MnDOT Pilot* study.[72] This case study involved developing adaptation options for an existing three-cell culvert (the "Base Case" in the figure) that the research team found to be inadequately sized to handle projected peak stream flows. Adaptation options tested included adding two additional culvert cells (Option 1), the same coupled with upstream floodplain enhancements (Option 2), or replacing the culvert with a bridge (Option 3).

[72] See also the *TEACR Economic Assessments* study for an example of a climate stressor-damage relationship curve for a culvert in a coastal setting.

The value of the climate stressor is typically shown on the horizontal axis of climate stressor-damage curves. For each design option, Figure 34 relates the flood elevation of the stream to

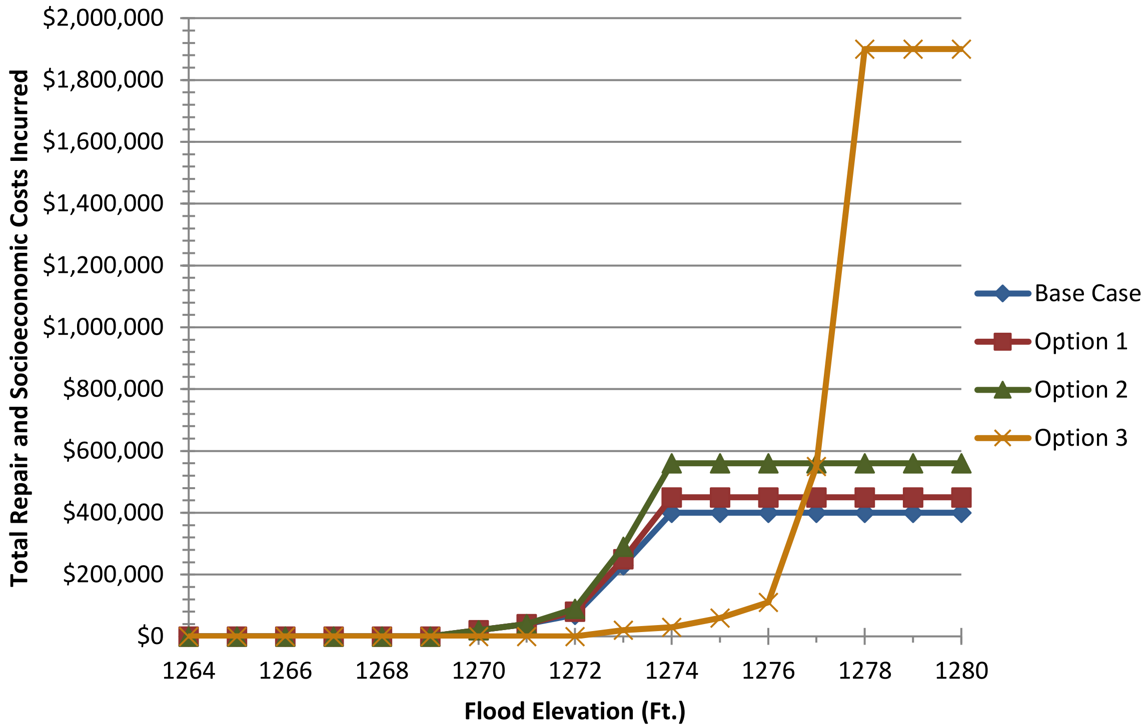

FIGURE 34: EXAMPLES OF CLIMATE STRESSOR-DAMAGE RELATIONSHIP CURVES FOR MNDOT CULVERT 5722 AND ITS ADAPTATION MEASURES.

Source: *MnDOT Pilot* study.

the estimated costs should the water reach that elevation. The metric for the climate stressor will vary depending on the type of asset being studied and its setting: it could be a flood elevation, flood depth (in which case, the curve is often called a "depth-damage curve"), stream discharge, temperature, etc.—whichever metric is best for capturing how damage to the asset changes as the intensity of the climate stressor changes.

The value of the expected damage costs are shown on the vertical axis of climate stressor-damage curves. The dollar values shown in the label on the vertical axis include both repair and socioeconomic costs.[73] Climate stressor-damage relationship curves can be drawn using either

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[73] In this case study within *MnDOT Pilot* (the District 6 - Culvert 5722 case study), socioeconomic costs included (1) the value of the incremental travel time costs to motorists from the detour, (2) the additional vehicle operating costs to motorists from the (lengthier) detour route, and (3) the potential cost of injuries to drivers and passengers due the damaged facility. The case study did not estimate possible property damage attributable to upstream pooling caused by the facility or enhanced downstream flooding ushered in by better conveyance of flows with the adaptation alternatives. Such costs, however, could also be included in the climate stressor-damage curves, if desired, along with any other broader economic impacts of flooding exacerbated by the facility.

only repair costs or, as shown here, both repair and socioeconomic costs that have been summed together. The types of costs to include in a climate risk-enhanced economic analysis are ultimately up to the agency conducting the analysis. In the case studies in the *MnDOT Pilot* study, two economic analyses were actually conducted for each asset, one including only costs to the agency and the other both costs to the agency and users, to see if there was a difference in the conclusions reached. Conducting these two types of analyses necessitated the use of two sets of climate stressor-damage relationship curves.

Damage costs rise as the value of the climate stressor increases (i.e., the higher the flood elevation). However, the rate of rise and the point at which it occurs vary depending on the design option. Each option has its own distinct curve depending on the unique interaction between the floodwaters and the facility. Engineering judgment and analysis is required to understand exactly how a specific asset will fail when subjected to increasing values of a climate stressor[74] and engineering cost-estimating techniques are then required to estimate repair (direct) costs. In the example, Options 1 and 2 experience greater impacts and incur higher costs at lower flood elevations than does Option 3.

Generally, when graphs are arranged as shown in Figure 34, the further to the right the curve for an adaptation option is relative to the base case, the more effective that adaptation option is at avoiding climate impacts and damage costs. The area between the base case curve and the adaptation option curve can be thought of as a preliminary measure of the benefits offered by the adaptation option.[75] A full understanding of the benefits of the adaptation, however, requires an understanding of the probability of reaching a given climate stressor value, a topic discussed in Section 6.3.4.2 Techniques for Linking Event Probabilities and Damage.

Curves may eventually plateau toward the right side of the graph. The plateau indicates the point at which total failure of the facility is reached. Generally, the higher the initial construction cost of the facility, the higher the ultimate damage costs can reach (i.e., the higher the plateau).[76] Climate stressor-damage relationship curves should always be extended out to

[74] Note that there is often some degree of uncertainty in precisely how assets will fail when subjected to a climate stressor. To deal with this uncertainty, it may be worth conducting a sensitivity test to see to what degree the uncertainty affects the conclusions. This would involve develop multiple plausible climate stressor-damage relationship curves based on various plausible failure mechanisms, each of which would be run through the economic analysis separately.

[75] The measure of benefits will include only direct benefits if only direct costs are included on the graph and will include both direct and indirect benefits if both direct and indirect costs are included. See Section 12.4.3.1, Types of Benefits, for a review of what typically constitutes direct and indirect benefits.

[76] It is assumed that damaged facilities are restored to their original design, a typical assumption when constructing climate stressor-damage curves. Also, note that the damage costs from a complete loss event do not necessarily need to meet or exceed the initial construction costs. This is because particularly durable elements of the facility may be able to withstand even the strongest weather events and may be salvageable for use in the repairs.

the point of complete failure of the asset to ensure that possible costs from very large storms are accounted for when calculating expected lifecycle costs in later steps.

One important thing to keep in mind is that climate stressor-damage relationship curves do not change as climate changes—they are fixed based on the design of the facility. Instead, the probability of climate events, and their associated damage, changes with climate change. To that end, one of the key observations from the graph in Figure 34 is that while Option 3 better minimizes costs for (the more frequent) smaller flood events, should a (rarer) particularly large flood event occur that is sufficient to severely damage the bridge, the costs with this option will be much greater. Estimating the number of times each flood elevation will be reached over the asset's design life (based on flood probabilities) will help to determine which design option is ultimately the most cost-effective.

When there is significant uncertainty in the failure mechanism of a particular asset, it is wise to consider sensitivity tests of different climate stressor-damage relationships to help determine the robustness of the results of the economic analysis. In the *TEACR Economic Assessments* study, FHWA tested the sensitivity of damage curve assumptions by re-running the analysis using alternate climate stressor-damage curves. The sensitivity of the results under the different damage curve assumptions demonstrates the importance of developing accurate climate stressor-damage relationships.

The next section describes techniques to determine the probability of reaching different climate stressor values and combining that information with the climate stressor-damage relationship curves to calculate the expected weather-related costs over the asset's design life.

6.3.4.2. Techniques for Linking Event Probabilities and Damage

Climate stressor-damage relationship curves provide an estimate of the costs should an asset be impacted by a climate stressor of a certain magnitude. However, the curves do not answer other key questions such as:

- What is the likelihood of a weather-related event occurring during the asset's lifespan and actually causing those costs to be incurred?
- How many damaging events might the asset be exposed to over its lifespan?
- What is the timing of those events?

Each of these questions is related to weather event probabilities and must be addressed to accurately estimate a design option's lifecycle weather-related costs.

Probabilities are used to state the chances that a weather-related event of a certain magnitude will happen within a given time period (typically, annually). In engineering applications, probabilities are most often expressed as percentages (e.g., a 1 percent annual chance flood) or as return periods (e.g., a 100-year flood).[77] Climate change will gradually change the probabilities of weather-related events as time goes on. Figure 35 provides an illustrative example from the *TEACR Economic Assessments* study. The lines on the graph show the probability that a given storm surge elevation will be exceeded in a particular year. As is expected, the graph indicates that the higher the surge elevation, the lower the probability it will be exceeded. Each colored line indicates the year for which the probabilities are captured. The lines shift to the right in the future indicating that, as sea levels rise, the probability of exceeding any given surge elevation will increase.

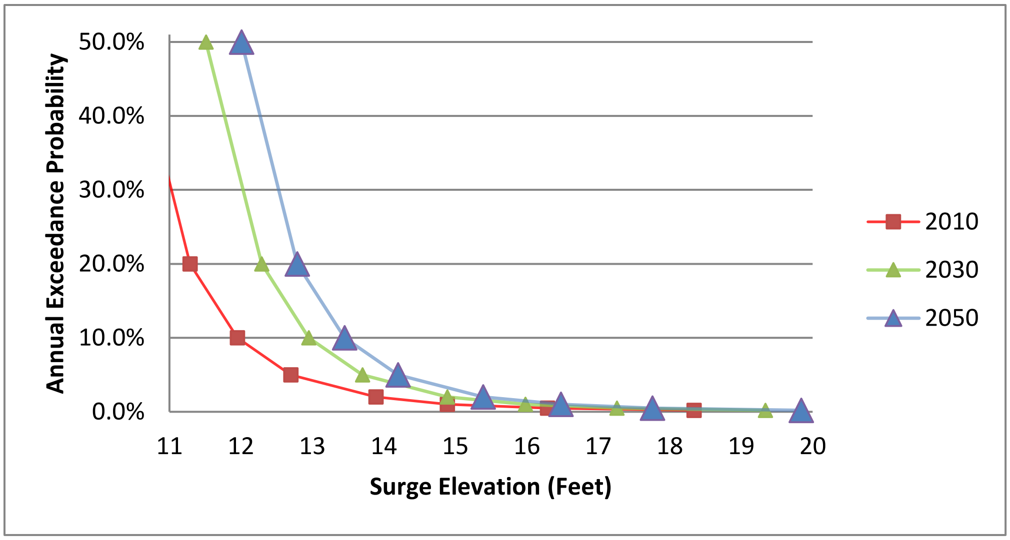

Figure 35: Illustration of Changing Storm Surge Elevation Probabilities Over Time for a Single Sea Level Rise Scenario.

Source: *TEACR Economic Assessments* study.

The probability of each climate scenario should be treated separately in economic analyses. The probabilities of future weather-related events can be calculated using projections obtained or derived from climate models. Most of the same statistical techniques used to determine probabilities from historical data can also be applied to future projections. Note, however, an important conceptual point that must be kept in mind when working with probabilities developed from climate projections: they are conditioned on the assumptions of the climate scenarios and models used to generate the projections. This means that these probabilities (referred to as "conditional probabilities") will only hold true if the greenhouse gas emissions and other assumptions involved in a given scenario come to pass; they are not the absolute probability that an event will happen in the future given the full range of possible future emissions trajectories. Given this, climate risk-enhanced economic analyses should be

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[77] Note that the 1 percent annual chance flood and the 100-year storm are two ways of saying the same thing. Many favor using the "x percent annual chance storm" terminology because the "x-year storm" terminology can be somewhat misleading, implying that a storm of that magnitude will not come again for x years.

undertaken separately for each climate scenario of interest and the results reported out separately (BCRs, NPVs, etc.) for each scenario as well.

When calculating probabilities for climate risk-enhanced economic analyses, practitioners should calculate the probabilities for a variety of return periods, not just one or two, so that a probability distribution can be created. Figure 35 is an example of one way a probability distribution can be displayed. Probability distributions are used to ensure that the costs from all possible event magnitudes are considered when estimating lifecycle weather-related costs. Separate probability distributions should be developed for a variety of future out-years over the life of the project. The *TEACR Economic Assessments* study featured in Figure 35 shows three distributions: 2010, 2030, and 2050. Probability distributions can be thought of as shifting gradually every year as climate changes. A new distribution could be developed from climate projections for each year but, to save on effort, distributions are typically created for only a handful of out-years and interpolated for the intervening years.

Once probability distributions have been estimated, the next step is to link the probability of each event with the costs shown in the climate stressor-damage relationship curves so that an estimate of lifecycle weather-related costs can be developed. Two different analytical techniques can be used: a Monte Carlo analysis and the area under the curve (AUC) approach. Although they differ in methods used, both techniques provide a similar solution. There are two additional techniques that can practitioners can use for situations where probability information is difficult to obtain: a scenarios approach, and the hybrid Monte Carlo/AUC and scenarios approach. The sections below provide an overview of each of the different techniques (Table 19 lists the method that was used on each climate risk-enhanced economic analysis case study completed to date).

Monte Carlo Analysis

Monte Carlo analyses address the uncertainty in timing and magnitude of future weather events by creating storylines of possible weather events over an asset's lifespan. Each storyline, known as a simulation, entails a different pattern of weather events affecting the asset. For example, one simulation may involve a strong damaging weather event impacting the asset early in its lifespan and only weak insignificant weather events thereafter. Another simulation may assume just the opposite: a series of weak weather events early in the design life and then a strong damaging weather event toward the end of it. Yet another simulation may entail a series of moderately damaging weather events impacting the asset throughout its lifespan. Many different weather event patterns are possible in the real world and Monte Carlo analyses use thousands of possible simulations to capture the range of possibilities.

Each simulation is developed using the probability distributions discussed earlier. For each time period of a simulation, a computer program is used to select randomly a weather event from that period's probability distribution.[78] More than likely, a weaker event will be chosen since the probability of picking it is higher. Nonetheless, selection of a strong event is possible as well; it is just less likely. The process then repeats in the next time period using its probability distribution. If climate change has shifted the distribution to increase the probability of stronger events, there is a greater chance that a stronger event will be chosen than in the time period before. The process is repeated for each time period in the project's lifespan. A simulation is then created by stringing together the events selected for each period. The computer program then iterates the same random selection process to create additional simulations. Each simulation will be different due to the randomized selection of events.

Direct and indirect weather-related costs are brought into the Monte Carlo analysis by referencing each design option's climate stressor damage relationship curve. For each weather event selected in a simulation, the corresponding cost value for that magnitude of event is read off the climate stressor damage relationship curve.[79] The cost value is then discounted, depending on how far in the future the event is projected to occur. Because of discounting, damaging weather events that are assumed to occur sooner will raise lifecycle weather-related costs more than if those same events were assumed to occur later in an asset's design life: this is why the timing of events is important. The discounted costs from each weather event in the simulation are then added to produce a lifecycle weather-related damage cost estimate for that simulation.

Each of the thousands of simulations from the Monte Carlo analysis will have its own estimate of the lifecycle weather-related damage costs to the asset. Simulations that involved only weaker weather events will have relatively low estimates while simulations that entailed an unusually high number of strong weather events will have higher estimates. The majority of simulations will likely be somewhere in between, reflecting the probabilities of the weather event inputs. The cost estimates from each simulation can be compiled into a distribution showing the probabilities of a particular design option reaching various lifecycle weather-related damage costs under a given climate scenario.

The average value from the distribution is the most likely estimate of what the lifecycle weather-related costs will be; this is the value typically taken forward and used when calculating the benefits of the adaptation options. The distribution can also be used to determine a confidence interval around the average value (or any other value) and to state the

[78] Note that various time steps for the analysis are possible (annual, monthly, etc.) depending on the needs of the project. Care must be taken, however, to ensure that the time step chosen matches the probability distribution used (e.g., one should not use a probability distribution of annual exceedance to select weather events on a monthly time step).
[79] Note that it is possible to use different climate stressor-damage relationship curves for different out-years. This should be done if the costs of impacts are expected to change in the future due to anticipated real (inflation-adjusted) changes in material and labor costs, changes in indirect costs (for example, due to projected changes in traffic volumes), weakening of the asset as it ages, etc.

probability that lifecycle weather-related costs will be above/below a certain amount. The *TEACR Economic Assessments* study and the *GC2 Culvert* study provide examples of how a Monte Carlo analysis can be applied to climate change risk-enhanced economic analyses.

AUC Approach

The AUC approach is an alternative technique for estimating a design option's lifecycle weather-related costs. Some practitioners believe that the approach is easier to implement than a Monte Carlo analysis. When done properly, the AUC approach is capable of producing results that are similar to the average value output from a Monte Carlo analysis. One disadvantage is that the approach produces only a single estimate of lifecycle weather-related costs, not a probability distribution like in a Monte Carlo analysis. Thus, confidence intervals surrounding the cost estimate and probabilities of costs being above/below a value of interest are not available if using this technique. Figure 36 provides a conceptual graphical overview of the AUC approach.

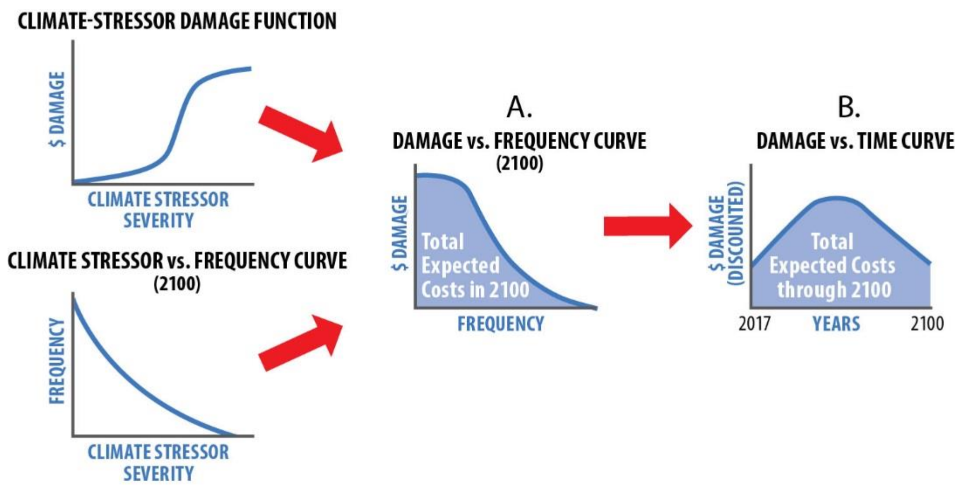

FIGURE 36: CONCEPTUAL OVERVIEW OF THE AUC APPROACH.

As shown on the left side of Figure 36, the AUC approach makes use of the same inputs as a Monte Carlo analysis, namely, climate stressor-damage functions for each design option and a set of probability distributions for different out-years and climate scenarios (the climate stressor versus frequency curve in the figure). The first step in an AUC analysis is to translate the climate stressor-damage relationship curve into a weather event probability-damage relationship curve (item A in Figure 36). Essentially, this involves changing the x-axis on a typical climate stressor-damage relationship graph from showing the magnitude of the climate stressor to showing the probability of that climate stressor value being reached. This change can be accomplished using the probability distribution, which relates event magnitudes to their probabilities. Figure 37 provides an example of a weather event probability-damage relationship curve from the *TEACR Economic Assessments* study. Note this curve is a step function but smooth curves are also possible. Since weather event probabilities will change over time due to climate change, each out-year in the analysis will have a different weather event probability-damage relationship curve. It is generally only necessary at this point, however, to create these curves for a few out-years as values for intervening years can be interpolated later on.

The next step in the AUC analysis is to calculate the area underneath each out-year's weather event probability-damage relationship curve. The resulting area value represents the expected weather-related costs for the design option in the given out-year. In Figure 36, this is indicated conceptually for a single out-year, 2100, by the blue shaded area under the curve in part A.

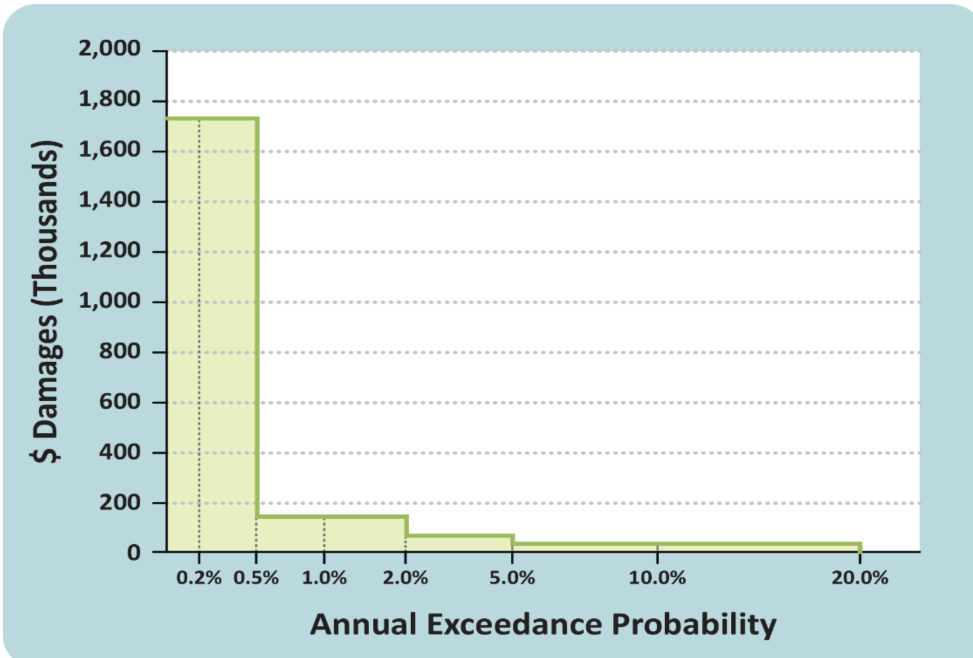

FIGURE 37: EXAMPLE WEATHER EVENT PROBABILITY-DAMAGE RELATIONSHIP CURVE FOR A SINGLE OUT-YEAR.

Source: *TEACR Economic Assessments* study.

As with Monte Carlo analyses, future weather-related costs next need to be discounted, depending on how far into the future the event is projected to occur. Then, the discounted costs can be plotted on a new graph showing expected costs over time. Interpolation is likely to be needed between out-years. An example from the *TEACR Economic Assessments* study that used linear interpolation between the out-years is shown in Figure 38. Typically, as climate changes, annual (non-cumulative) weather-related costs can be expected to rise over time resulting in a steadily upward sloping curve. However, when discounting is considered, the curve may actually take on more of an inverted "U" shape (as depicted in Figure 38) since costs incurred in the distant future will be reduced more greatly by the effects of discounting. To determine the design option's lifecycle weather-related damage costs, the area under the costs-over-time curve is calculated. This is illustrated conceptually by item B in Figure 36. The resulting weather-related damage cost estimate can then be carried forward and used to calculate the benefits of the adaptation options. Example applications of the AUC approach can be found in the *TEACR Economic Assessments* study and the *MnDOT Pilot* study.[80]

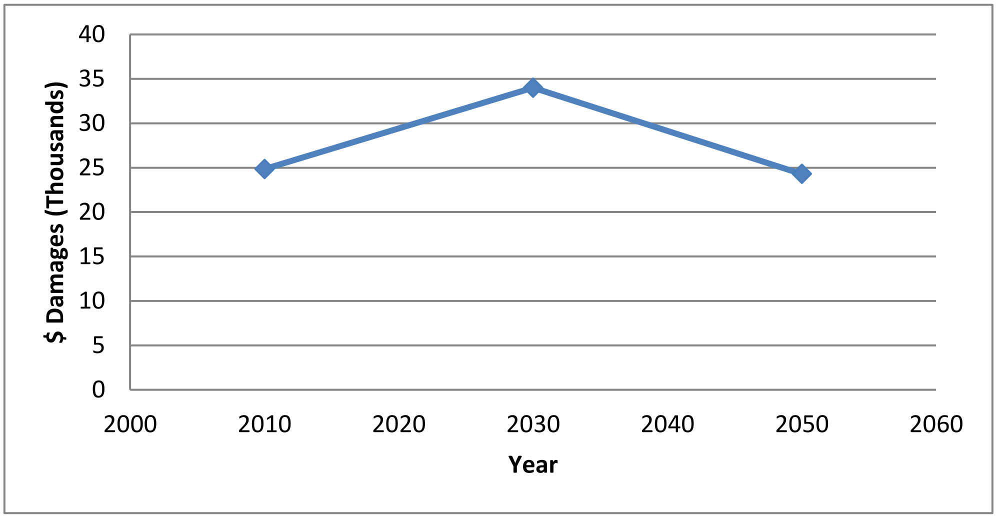

Figure 38: Example of Curve Showing Expected Annual (Non-Cumulative) Discounted Weather-Related Damage Costs.

Source: *TEACR Economic Assessments* study.

As mentioned above, the AUC method and Monte Carlo analysis work well if probability data on weather-related events are available. If probability data are not available, a modified version of the general approach used for Monte Carlo analysis and the AUC method can be undertaken. This modified approach is called the scenarios approach. If multiple climate stressors affect an asset and some stressors have probability information while others do not, the scenarios approach can be combined with a Monte Carlo analysis or AUC method in a hybrid approach. Each of these techniques is described in the sections that follow.

Scenarios Approach

Probabilistic projections of climate stressors are not always readily available or easily calculated for a given climate scenario. This is often the case with secondary stressors where climate change may affect one or more variables, which then acts through other mechanisms to affect the asset. For instance, climate variables like precipitation and temperature are key factors in determining the probability of wildfire, a secondary stressor, but there are many additional factors that are difficult to assign probabilities to, which must be considered as well (e.g., ignition source, vegetation type, likelihood of suppression). Geohazards often present a similar challenge. For example, landslides may be influenced by precipitation but other mechanisms also usually affect the likelihood of a slide occurring. Determining how a slope may respond to a

[80] *MnDOT Pilot* made use of a software tool called COAST, which performs the calculations required for AUC analysis.

given amount of precipitation often takes a lot of upfront research to link slide movement with rainfall, an effort that can be time- and cost-intensive.

When probability data on hazards is hard to come by, a scenarios approach can be taken to accomplish an economic analysis. With the scenarios approach, a series of plausible scenarios of weather-related event occurrences are created based on professional judgment. Rather than using, for example, a Monte Carlo analysis to develop a simulation/storyline of future events, the scenarios indicate, a priori, the frequency, magnitude, and timing of the hazard based on what is physically plausible. The scenarios should be set up to bound the range of possible outcomes. In other words, there should be an optimistic scenario, a pessimistic scenario, and intermediate scenario(s). The number of scenarios to include depends on the unique characteristics of the site and the project.

Once scenarios are developed, the performance of the base case design and adaptation options can be evaluated under each scenario. Climate stressor-damage relationship curves can be used to assign costs to each event, just as with the Monte Carlo and AUC methods. Those costs can then be discounted, depending on the year when the event is projected to occur. The discounted costs are then summed to develop a lifecycle weather-related cost estimate for the given design option under the selected scenario. Doing this for all adaptation options across all scenarios results in a compendium of lifecycle weather-related cost estimates for each design option under each scenario—information that can be used to derive the benefits of various adaptation options.

An example application of the scenarios approach can be found in a case study within the *WFLHD/AKDOT&PF Pilot* study. This case study investigated possible future movements of a landslide along Denali Park Road in Denali National Park due to projected changes in precipitation and temperature.[81] The scenarios developed for this project considered the possible timing of future slides and their magnitude, defined in terms of the volume of slide material. Using the scenarios approach, the project team was able to develop an understanding of the cost-effectiveness of various adaptation options despite the uncertainty of future slide behavior.

Hybrid Monte Carlo/AUC and Scenarios Approach

Some assets are exposed to multiple interacting climate stressors. In these cases, it may be possible to derive the probabilities of one climate variable but not the other. A hybrid Monte Carlo/AUC and scenarios approach can be used to determine the benefits of adaptation options in these situations. With the hybrid method, the scenarios approach is first used to generate a set of scenarios for the climate stressor whose probability is difficult to determine. As discussed above, these scenarios indicate, a priori, the occurrence of the climate stressor of interest.

[81] A scenarios approach was taken because, at the time of the analysis, it was unclear how responsive the slide was to precipitation (data was being collected but was not yet available). In addition, the distribution of permafrost on the slope and its characteristics were unknown due to access limitations.

Next, using the climate stressor whose probability is known, a Monte Carlo or AUC analysis is run for each of these scenarios. In essence, the scenarios are used to set an assumed condition, off of which the Monte Carlo or AUC techniques work.

An example application of the hybrid approach can be found within the *TEACR Culvert* study. In the case study, precipitation/discharge probabilities were known but wildfire probabilities were unknown. Thus, the research team developed, for the watershed of interest, plausible scenarios of wildfire timing and recurrence frequency over the lifespan of the culvert. These scenarios set the condition for whether the watershed was in a burned state—a condition that was found to greatly enhance discharges and debris/sediment loads at the culvert for approximately ten years after a fire. The research team then ran a Monte Carlo analysis on each wildfire scenario to understand the possible frequency, magnitude, and timing of heavy precipitation events in the watershed, including the chances of heavy precipitation events occurring while the watershed was burned out. Whenever a heavy precipitation event occurred during the burned period, special discharge probability distributions and climate stressor-damage relationship curves were used that, essentially, increased the costs incurred when compared to a similar event happening during normal (non-burn) watershed conditions. By employing the hybrid approach, the research team was able to account for the effects of fire and changes in rainfall patterns to determine which adaptation option was most cost-effective, despite the substantial uncertainty surrounding future wildfire patterns.

6.3.4.3. Comparison of Techniques

A summary of the advantages and disadvantages of each of the techniques can be found in Table 21.

The availability of probability data for the climate stressors of interest should help practitioners determine the technique to employ.

- *Probability data are available for all of the climate stressors of interest:* either the Monte Carlo analysis or the AUC approach
- *Probability data are available for one, but not all, of the climate stressors of interest:* hybrid Monte Carlo/AUC and scenarios approach
- *No probability data are available for any of the climate stressors of interest:* scenarios approach

If probability data are available for all of the climate stressors of interest, the biggest decision facing practitioners with respect to techniques is whether to use Monte Carlo analysis or the AUC approach. Both techniques will provide similar solutions. This is demonstrated in the *TEACR Economic Assessments* study where a culvert exposed to storm surge was analyzed using both techniques and the results found to be comparable. The question of which technique to use boils down to a tradeoff between the richness of the outputs and the level of effort/staff skills required. As summarized in Table 21 and discussed above, Monte Carlo analysis is capable of creating more sophisticated outputs such as confidence intervals, the probabilities a

BCR/NPV exceeds (or is less than) a given threshold, the ability to look at the outputs from specific simulations, etc. The AUC approach does not afford these possibilities. On the other hand, Monte Carlo analyses require more knowledge of statistics and are more computer intensive than AUC analyses. It is up to practitioners to decide whether having access to the richer outputs of a Monte Carlo analysis warrants the additional efforts required by this technique.

TABLE 21: COMPARISON OF TECHNIQUES FOR LINKING EVENT PROBABILITIES AND DAMAGE

Technique	Advantages	Disadvantages
Monte Carlo Analysis	• Can be used to provide point estimates and associated confidence intervals of total costs, BCRs, and NPVs • Enables one to evaluate the probability that a BCR or NPV is above a certain critical threshold (e.g., the probability that the BCR is greater than one or that the NPV of the adaptation is greater than zero) • Offers the ability to compare the sensitivity of the findings to the timing and intensity of storm events through investigation of individual simulations	• Requires information on the probability of weather-related events • Requires more familiarity with statistics • More computationally intensive
AUC Approach	• Requires less familiarity with statistics • Less computationally intensive	• Requires information on the probability of weather-related events • Can provide only point estimates of benefits, BCRs, and NPVs, which may engender a false sense of confidence in the findings • Prone to errors based on how one specifies the curves and calculates the areas underneath them • Limited ability to explore the sensitivity of the findings to the timing and intensity of storm events
Scenarios Approach	• Does not require information on the probability of weather-related events	• Cannot incorporate weather-related event probabilities • Findings are constrained to the limited number of weather event scenarios/simulations tested • Can provide only point estimates of benefits, BCRs, and NPVs, which may engender a false sense of confidence in the findings
Hybrid Monte Carlo/AUC and Scenarios Approach	• Does not require information on the probability of weather-related events for all relevant climate stressors	• Findings are constrained to the limited number of weather event scenarios/simulations tested • Can provide only point estimates of benefits, BCRs, and NPVs, which may engender a false sense of confidence in the findings

6.4. Economic Analyses Knowledge Gaps

Greater engineering knowledge is needed on climate stressor-damage relationships. Engineers usually have not focused on analyzing physical damage to assets given climate stressors. More research is needed on damage mechanisms and thresholds to inform the development of climate stressor-damage relationship curves. For instance, climate stressor-damage relationship curves may be developed for chronic climate stressors but would require greater engineering knowledge of the rate of asset deterioration over time under a climate condition. Close cooperation with engineers and asset managers can help document the relationship between climate stressors and asset damage.

Additional studies on the costs and benefits of adaptation are needed. Practitioners have expressed a need for "default" values to be able to more easily quantify, in dollar terms, the costs and benefits of adaptation measures. However, this is not realistically feasible since many of these values are likely to be regionally or site specific. This need for default values stems from limited or difficult-to-access information on costs and benefits. Additional research and case studies on economic analyses of adaptation will help broaden the pool of knowledge of costs and benefits of adaptation.

Additional studies on how to quantify the environmental benefits of adaptation. Although some tools are available, benefits that are harder to quantify, such as environmental benefits, do not have standard or easy-to-use tools or methods. Valuation of these additional benefits may increase the monetized benefits of the adaptation measure and affect the economic analysis results. While the environmental benefits of adaptation measures such as fish passageways can be qualitatively considered as part of additional considerations (see Chapter 7), there is a desire in some communities to be able to provide an apples-to-apples, monetized evaluation of the environmental costs and benefits.

7. Evaluating Additional Considerations

On the surface, it may seem reasonable to select adaptation options based on the results of the economic analyses. One might reason that if any of the adaptation measures would result in benefits that outweigh the costs, then adaptation should occur; and, whichever option achieves the best result at the lower cost should be the preferred option.

However, the decision to invest in adaptation is not an isolated one. Transportation agencies need to invest their scarce resources so that, on a whole, the suite of their investments decisions are achieving their agency priorities. Thus, the decision of which adaptation measure to choose—and even whether to adapt at all—needs to take into account more than just cost-effectiveness.

These additional considerations beyond engineering- and cost-effectiveness include considerations related to:

- Environment
- Economy
- Society
- Governance
- Systematic considerations
- Agency priorities

What might be optimal from a purely cost-effectiveness perspective might not be optimal for these other considerations. Furthermore, not all items that need consideration are able to be fully monetized and therefore are not captured in the economic analysis. Consideration of these additional factors provide a more complete understanding of the full value and appropriateness of the adaptation measure to the agency and community. A summary of potential additional considerations is included in Table 22.

TABLE 22: SUMMARY OF ADDITIONAL CONSIDERATIONS

Focus Area	Additional Considerations
Environment	Adaptation measures may have effects on habitats and natural resources.
	Indicators may help quantify environmental impacts of adaptation measures.
Economy	Indicators of the asset's importance to the local economy can be used to understand the value of protecting the asset from climate change.
Society	Context-sensitive design can enhance the aesthetics and recreational uses of the project.
	Prioritize adaptation funding for assets that are vulnerable and serve emergency response services.

Focus Area	Additional Considerations
	Not adapting the transportation network can render disadvantaged populations more vulnerable to climate change.
	Implementation of adaptation measures can have negative impacts on disadvantaged populations.
Governance	Permit requirements may affect adaptation option development.
	Encroachments in regulatory floodplains and waters may require design modifications.
	Historic landmarks can be harder to modify for adaptation.
	Environmental permitting requirements for fish passage can affect the adaptation design.
	Variances may be needed to implement some adaptation strategies.
	Low risk tolerance and/or high pressure from the public for resilient infrastructure may contribute to the justification for funding adaptation.
	Liability concerns may limit an agency's ability to provide broader flood protection.
Systematic Considerations	The response of the surrounding natural environment to climate change may necessitate different adaptation strategies.
	Trends in vehicle traffic volumes have implications for adaptation planning.
	Criticality and redundancy in the transportation network are factors in adaptation investment.
Agency Priorities	Timing of capital funding availability for adaptation measures matters.
	Manage cumulative costs of adaptation across the system.
	Balance upfront costs of adaptation vs. costs of damages given no adaptation.
	Constructability and ROW issues are important for large adaptation projects.
	Consider the durability of adaptation strategies in the design of such measures.

After going through a thoughtful process to take into account additional considerations, practitioners may decide to modify the preferred adaptation option in some way, or to select a different adaptation option that is still cost-effective but that also provides broader benefits.

The remainder of this section expands upon the potential additional considerations for adaptation measures that were evaluated in the case studies.

7.1. Environment

Practitioners should consider the impact of adaptation strategies on the surrounding natural environment. Doing so can help enhance the overall sustainability of the project, and in some cases, it may be required by environmental legislation or permitting processes. Impacts of adaptation measures on the environment may include either unintended consequences or added value. Lessons learned from the case studies include:

Adaptation measures may have effects on habitats and natural resources. For instance, in *GC2 Bridge Approach-Storm Surge,*[82] FHWA recognized that scour countermeasures could have negative impacts on the environment, for example by disturbing aquatic vegetation beds, and also disrupt traffic flow while the countermeasure is being installed. Therefore, FHWA determined that these negative impacts should be carefully considered when selecting adaptation options. Preferred adaptation measures could be ones that have minimal short-term construction and long-term ecological impacts. Natural and nature-based solutions (sometimes called "green infrastructure") can also provide resilience while enhancing ecosystems. The FHWA [Green Infrastructure Techniques for Coastal Highway Resilience]() webpage provides more information.

Indicators may help quantify environmental impacts of adaptation measures. For instance, in the *NYSDOT Pilot,* NYSDOT considered 15 ecological factors when prioritizing culverts for adaptation, such as: upstream and downstream culvert density; percent impervious surface in watershed upstream of culvert; percent natural and conserved land cover in riparian area of upstream and downstream functional network; number of rare fish in upstream and downstream functional network; and brook trout locations in upstream and downstream functional network. NYSDOT used the indicators to identify culverts that were ecological priorities and thus may warrant different or modified adaptation solutions.

7.2. Economy

To supplement the quantitative economic analysis (see Chapter 6), additional impacts to the broader economy may be qualitatively evaluated. These additional economic considerations may have been outside the scope of the quantitative economic analysis for a variety of reasons (e.g., insufficient information to quantify, complexity of the analysis beyond the scope of the assessment), but identified as important to factor into project decision-making. For instance, an economic analysis that did not quantify indirect costs of climate impacts to the economy could qualitatively evaluate these costs. A key lesson from the case studies is:

Indicators of the asset's importance to the local economy can be used to understand the value of protecting the asset from climate change. For instance, in the *Caltrans Pilot,* Caltrans identified indicators of potential needs or reliance for service of the asset, such as population or number of commercially zoned parcels within a given distance of the roadway. Caltrans used the indicators to help understand the impact that damage to a transportation asset would have

[82] Throughout this section, case studies are referred to by an abbreviated title. For a full list of the case studies referenced in this report and their complete titles (with hyperlinks), see Appendix A: List of Case Studies.

on parts of the economy that rely on the asset, without conducting a rigorous economic analysis.

7.3. Society

As with all transportation projects, it is critical to consider the impacts of an adaptation measure to society. Some considerations for society include the impact to surrounding land owners; the necessity of the asset for emergency response; impacts to disadvantaged communities; and effects on regional mobility. Each of these issues are discussed in more detail in this section.

7.3.1. Impact to Surrounding Land Owners

Residents and businesses located near the transportation facility have an attachment to, and possibly an economic investment in, the project area. It is important to consider how the potential adaptation strategies would impact them. Thinking through this consideration can help minimize potential future opposition to the project from the community. The case studies resulted in the following lessons learned:

Context-sensitive design can enhance the aesthetics and recreational uses of the project. In the *GC2 Bridge Approach-Storm Surge* study, aesthetics and recreational use were identified as a key issue for public and stakeholder acceptance of adaptation measures. In some locations, transportation facilities are located in highly visible areas, such as beaches or nature areas. In these locations, the use of a context-sensitive treatment that does not limit the usage of the nearby recreational areas or create an "eyesore," might be better received by the community. For instance, considerations may include avoiding the use of armor stone due to its potential to both provide a hazard to pedestrians and its unsightly nature. Adaptation measures should consider the use of bioengineering treatments or subterranean measures.

7.3.2. Emergency Response Needs

The operation of emergency response services is always important, but it is especially vital after an extreme weather event. For this reason, special attention should be provided to transportation assets that serve emergency response needs to ensure they are resilient to future events.

Prioritize adaptation funding for assets that are vulnerable and serve emergency response services. When deciding whether or not to implement an adaptation measure, consider the role of the asset in ensuring emergency response services. For example, in the NYSDOT Pilot study, NYSDOT considered if a hospital, fire station, police station, or ambulance service was located on the roadway segment that would experience reduced access when flooded or closed due to culvert failure. If one of these services was located on the roadway segment, then that segment would be prioritized for adaptation funding. If complete resilience of the transportation facility cannot be guaranteed, then it may be necessary to pair a built adaptation measure with updated evacuation plans and increased emergency response coordination, as was done in the GC2 Highway Surge study.

7.3.3. Effect on Disadvantaged Populations

The definition of disadvantaged populations will vary from place to place but it may include the elderly and the very young, low-income residents, physically or mentally disabled, those without a household vehicle, non-native English speakers, etc. The impacts of transportation service disruption and adaptation measures may be felt more acutely by this population, and therefore it is important to specifically consider their needs.

Not adapting the transportation network can render disadvantaged populations more vulnerable to climate change. For example, according to the *Sandy: Governor's Island Ventilation Building* study*,* closure of a major tunnel due to sea level rise and storm surge could potentially lead to increased travel time and cost for populations it serves, many of which are below the poverty line. Also, because the tunnel is a designated emergency evacuation route, its closure may have greater consequences for disadvantaged communities. Transit service disruptions may disproportionately affect low-income populations because they may not have alternate travel options. For example, in the *Sandy: Metro-North Railroad* study, MTA determined that the transit line likely serves a share of commuters without the financial means to drive to work on a regular basis. In the event that an extreme weather event disrupted transit service, these commuters would be reliant on replacement bus service and may have to forgo wages if alternative transportation is temporarily unavailable.

These disproportionate impacts on disadvantaged populations should be considered when prioritizing facilities for adaptation. Some metrics used to determine the criticality of an asset, and thus prioritize it for adaptation, can overlook importance from a disadvantaged population perspective. For example, methods to assign importance of transportation assets based on the value of goods and services, number of people served, and economic activity serviced by the asset, may not take into account the importance of certain highway routes or transit modes for evacuation of disadvantaged populations.

Implementation of adaptation measures can have negative impacts on disadvantaged populations. Similar to the consequences of climate impacts, disruptions to the transportation network during adaptation implementation, such as when the project is under construction, may also disproportionately affect disadvantaged populations. To mitigate the impact, it may make sense to consider aligning construction with other repair, retrofit, and construction activities.

7.4. Governance

The governance context is an important reality to keep in mind when evaluating adaptation measures. Consider the governance considerations of adaptation measures and implementation, such as plans or actions by other entities; permitting/regulatory restrictions; and local political priorities and sensitivities.

7.4.1. Permitting/Regulatory Process

It is important to consider the permitting and regulatory process during identification and design of adaptation measures to ensure that implementation is feasible. Obtaining construction permits and abiding by regulatory processes for adaptation measures that are unconventional may present challenges. Permitting challenges may limit the range of available adaptation strategies and/or require increases in the costs and time for implementation. Permitting and regulatory requirements may encourage an agency to select the path of least resistance when identifying adaptation measures, which in some cases may result in a less strategic, shorter term fix to climate change issues. Lessons from the case studies may help practitioners think through potential permitting and regulatory requirements.

Permit and regulatory requirements may affect adaptation option development. For example, some states have requirements for construction in or alongside streams to ensure that fish passage is not impeded (e.g., by small culverts). Fish passage could be impeded by high flow velocity or shallow water depths. Regulatory requirements may dictate the size (waterway opening) of new or replacement drainage structures. Designers may need to replace a culvert with a larger structure for permit reasons, or may be required to replace the culvert with a size that maintains the existing restriction of flow downstream. For example, the *MnDOT Pilot* and *NYSDOT Pilot* research teams both evaluated culvert adaptation options in consideration of climate change needs and considered environmental permitting/fish passage requirements. In each of the studies, the research team discovered that the projects designed to meet current environmental regulations exceeded the size requirements for handling future flows alone.

Coastal infrastructure adaptation options such as armoring or realigning transportation facilities can also be subject to multiple standards and permit applications from different regulatory authorities. As part of the *ODOT Pilot,* ODOT reviewed federal, state, and local land use regulations in order to understand the restrictions for potential coastal adaptation projects. Developing this deeper understanding allowed ODOT to think creatively about what it could accomplish.

Encroachments in regulatory floodplains and waters may require design modifications. In the *TEACR Culvert* study, Colorado DOT (CDOT) recognized that any adaptation options that would require raising of the roadway would result in an encroachment into a local river, which would cause significant impacts to FEMA regulatory floodplains and loss of regulatory waters with natural trout habitat. These impacts may require adaptation design modification, such as the inclusion of reinforced concrete retaining walls to keep the slope fill out of the river.

Historic landmarks can be harder to modify for adaptation. Historic landmarks and the surrounding areas may have additional permitting and regulatory requirements. In the *GC2 Bridge Embankment-SLR* study, FHWA identified that there may be potential concerns with having a higher bridge block local sight lines to an adjacent national park and two ships which are National Historic Landmarks. Also, as encountered in the *GC2 Tunnel* study, subgrade remediation adjacent to historically significant buildings could lead to several technically challenging issues. Lastly, *MnDOT Pilot* considered removing a historic railing on a culvert structure when replacing a culvert with a larger one to withstand future streamflow. However, regulatory requirements for the project indicated that expansion of the existing culvert, rather than complete replacement, would provide a more permissible treatment in regards to the historic railing.

Variances may be needed to implement some adaptation strategies. Some permitting and regulatory agency processes have not been updated to accommodate the construction of adaptation strategies. For example, the TEACR Living Shoreline study found that in New York, obtaining the required coastal construction permits at the time would be more straightforward for a traditional armoring adaptation option than a living shoreline adaptation option. The study team desired to place a constructed marsh seaward of the existing seawall/revetment to moderate storm surges but that approach will encounter different, significant, and less commonly addressed regulatory issues. The study team identified that one way to address these issues may be with a special variance as a living shoreline demonstration project. The variance would be required to address two specific regulatory issues in the State of New York: activities seaward of mean high tide and filling of water bottoms. Since the development of the case study, the USACE authorized Nationwide Permit 54 that specifically addresses the construction and maintenance of living shoreline projects, which is expected to streamline the permitting process for such projects. However, it may have limited applicability to transportation projects due to restrictions on the size and length of projects to which it can apply.

7.4.2. Public and Political Considerations

Public and political pressure can be a strong driver of adaptation decision-making. It is valuable to think through the public and political response to adaptation strategies before selecting them as the preferred option.

Low risk tolerance and/or high pressure from the public for resilient infrastructure may contribute to the justification for funding adaptation. For example, after the impacts to transportation networks from Hurricane Sandy, some agencies adopted a very low risk tolerance for future extreme weather events and are building back stronger to minimize disruption from future events. It is important to note however, climate impacts do not need to occur in order for agencies to adopt a low risk tolerance. In such instances, an appropriate course of action may include conducting a proper analysis before the climate event occurs and communicating to the public ahead of time the planned adaptation measure and anticipated disruptions during implementation.

Additionally, high pressure from the public to reopen infrastructure quickly after an event may be a consideration. However, if an asset is damaged, then high pressure may cause the agency to rebuild in-kind quickly rather than taking the time to evaluate the most resilient or cost-effective approach under a changing climate. For example, the highway in the *TEACR Culvert* study was washed out in 1976 after a major flood event and rebuilt largely the same. In 2013, the road was washed out again and in order to get the road re-opened as quickly as possible, CDOT performed temporary emergency repairs. The emergency repairs allowed CDOT to reopen the roads but it also bought them time to assess the best course of action. In 2016, CDOT began to reconstruct part of the road and is factoring in climate resilience to the study's culvert as part of the permanent repair.

Liability concerns may limit an agency's ability to provide broader flood protection. In *GC2 Highway Surge*, the possibility of improvements to a road embankment for the purpose of providing flood protection to a nearby neighborhood was immediately ruled out because use of the roadway in this manner would exceed the overall design considerations and standards for the roadway. Additionally, the repurposing of any roadway as a flood protection structure will open the owner/agency up to additional liability concerns in the event that an extreme event breaches the roadway. Given that flood protection is not the primary function of a roadway and that a roadway will fall short of the design standards necessary for a flood protection structure, FHWA currently recommends against owner agencies pursuing this manner of adaptation.

7.5. Systematic Considerations

Transportation assets do not operate in isolation, as they are tied to their surrounding environment and are part of an interconnected transportation system. As with any transportation project, it is important to consider these settings when selecting adaptation strategies. Lessons from the case studies provide examples of systematic considerations for adaptation measures.

7.5.1. Asset's Relationship to the Surrounding Environment

It is important to consider the asset's relationship to its environment and how that environment may shift over time. The impacts of surrounding land use change may change the value or appropriateness of the adaptation strategy.

The response of the surrounding natural environment to climate change may necessitate different adaptation strategies. Barrier islands can essentially roll over and migrate toward the mainland in response to storms and sea level rise. This barrier island migration process has been likened to the tread of a bulldozer: the islands roll over themselves by retreating on the ocean side while extending on the lagoon side and while simultaneously moving vertically, keeping up with sea level rise. The morphological changes may raise the elevation of, or laterally relocate, the island. This change may necessitate raising the transportation asset or relocating the roadway laterally closer to the mainland. Alternatively, if the morphological changes do not keep pace with sea level rise, than the transportation agency and community may need to assess the impacts of losing not only the roadway but the entire barrier island. Barrier island migration was a key context consideration for *TEACR Roadway Surge.* Understanding these potential changes in the transportation facility's environment is critical when selecting an appropriate adaptation strategy.

7.5.2. Asset's Relationship to the Transportation System

Transportation networks do not operate efficiently when only some of the components are resilient to climate change. Considering only one asset at a time in vulnerability assessments and adaptation planning could result in the mischaracterization of overall adaptation needs or in stranded assets. For example, given that roads within a watershed might be served by a series of culverts, adapting only one culvert may cause more stress on downstream culverts. The case studies identified several considerations for the broader transportation system.

Trends in vehicle traffic volumes have implications for adaptation planning. Traffic volumes will evolve over time through shifts in population, land use, or loss of service on other major roadways. Increased traffic volumes might provide added impetus to enhance the resilience of the asset to climate change in order to ensure service is maintained or enhanced. On the other hand, if climate change negatively affects adjoining land use to the point where they are abandoned, the need for the asset within the larger transportation network may be diminished. An important consideration in transportation adaptation planning is the viability of the land uses served by the transportation facility. In the *GC2 Bridge-Storm Surge* study*,* a consideration was that the next significant storm surge may eliminate the land uses served by the study asset. If those land uses are not rebuilt, the need for the ramp may be lessened to the point that it may no longer be needed and expensive reconstructions or adaptation measures might not be necessary. Public involvement with nearby property owners and communities would likely be conducted if this scenario was being considered.

Criticality and redundancy in the transportation network are factors in adaptation investment. If alternate routes are already more resilient and serve as viable alternatives, then it may be less important to invest in adaptation of the asset. However, if a route is the only one available to a community without significant detours or if the capacity is needed for the overall system, then it may be more important to invest in adaptation of the asset. In the *Sandy: Governor's Island Ventilation Building* study, FHWA specifically selected the transportation asset (a tunnel ventilation building) for study and the development of adaptation options because its functionality is critical to the operation of the tunnel.

7.6. Agency Priorities

Transportation agencies also should consider funding availability, constructability, and durability/maintenance needs in the selection of adaptation strategies.

7.6.1. Funding Availability

Although the lifecycle costs from the economic analysis may demonstrate the long-term fiscal benefits of investing in adaptation that does not mean that funding for adaptation is available or immediately accessible.

Timing of capital funding availability for adaptation measures matters. The availability of capital funding for adaptation projects may range from near term to long term, or before or after an extreme weather event. For example, several of the facilities analyzed in the *Post-*

Sandy assessments were able to take advantage of emergency funding to increase their resilience. Agencies may consider the timing of funding availability when prioritizing plans for adaptation implementation. For example, it may be necessary to delay adaptation implementation until the asset's scheduled rehabilitation or reconstruction. Additionally, practitioners should ensure funding availability for increased or decreased maintenance needs under a changing climate.

Manage cumulative costs of adaptation across the system. While the cost premium of adaptation measures may be fairly low at a project level, costs of adaptation measures may add up since the effects of climate change will be systemic and statewide. Cumulative costs to adapt all assets can become unmanageable. *TEACR Pavement Shrink-Swell* and *TEACR Permafrost Thaw* studies considered that the cumulative cost premium will most likely impact the capital improvement or maintenance budget significantly at the district or state level. Using a proactive approach to preservation, maintenance, and renewal decisions will offset some of the budgetary constraints. In the *TEACR Culvert* study, the research team recommended a reactive adaptation approach be employed, considering the anticipated low probability of wildfire occurrence in the study watershed. If a wildfire does in fact occur, then adaptive measures would be taken to reduce future vulnerability of the culvert.

Balance upfront costs of adaptation versus costs of damages given no adaptation. An adaptation measure might be highly cost-effective over time, but the large capital outlay for construction in year one can still pose a challenge to many agencies. This is one reason why adaptation strategies may be cut during a value engineering[83] or practical design[84] process. If the adaptation options are costly, but losing the asset is costly as well, alternatives may include continued research of adaptation strategies and consideration of smaller, incremental adaptation measures. For example, in *TEACR Coastal Bridge*, elevating the bridge appears to be the best course of action that would guarantee survival of the asset during future storms. However, this option is costly. Meanwhile, there may be other adaptation strategies that reduce the risk of failure in lower levels of storm surge for less cost. For example, the Florida I-10 Bridge that was damaged in 2004 may have survived Hurricane Ivan if the connections were stronger. In such a situation, further study is warranted to determine if the less-expensive option might provide adequate levels of risk reduction.

7.6.2. Constructability and Durability/Maintenance

Constructability and ROW issues are important for large adaptation projects. Such considerations help to ensure that a proposed project is feasible to implement. In the *GC2 Bridge Approach-Storm Surge* study, FHWA considered how implementation of the scour

[83] A systematic process of review and analysis of a project, during the concept and design phases, that is conducted to provide recommendations for: providing the needed functions safely, reliably, efficiently, and at the lowest overall cost; improving the value and quality of the project; and reducing the time to complete the project.
[84] The practice of scoping projects to stay within the core purpose and need, expected to result in lower cost and improved value.

countermeasure can present constructability issues due to limited clearance under many low-lying bridges or due to limited or difficult access to the embankment slopes of shoreline. Retrofits to bridge foundations and difficult construction projects are complex and could result in the temporary closure of a structure, and this would be factored into the final selection of the course of action. Additionally, in the *ODOT Pilot* study, ODOT considered the potential need for construction outside of the existing right-of-way (ROW), and determined that the regulatory burden and cost to expand the ROW is high. This consideration would impact the final selection of the course of action.

Consider the durability of adaptation strategies in the design of such measures. In the *GC2 Bridge Approach-Strom Surge* study, FHWA considered the durability of scour countermeasures, especially in light of expected increases in the frequency and intensity of storm surge. In the *MnDOT Pilot* study, MnDOT considered whether a culvert adaptation option could provide both a sustainable platform for channel bed sediments and meet the low flow velocity and depth requirements for fish passage. From a long-term maintenance standpoint, MnDOT also considered how the selection of a bridge adaptation option would encumber the agency with an additional structure in need of regular inspections, while a culvert would have its own maintenance needs that may be more or less of a concern.

8. Monitoring and Revisiting as Needed

The frameworks tested by FHWA all contain final steps related to developing a facility management plan and revisiting the analysis in the future. This chapter discusses the reasons to implement a facility management plan. The chapter then explores how these analyses may need to be revisited over time due to changing priorities, facility use, and advances in climate science.

8.1. Develop a Facility Management Plan and Integrate into Asset Management

Once a course of action has been decided, a facility management plan can be developed to determine when to implement adaptation measures and ensure the project continues to perform as designed under changing climate conditions. The plan would include ongoing monitoring as the climate changes and require that corrective actions be considered. Lessons learned include:

Adaptive management can be a cost-effective way to ensure resiliency given an uncertain future. Adaptive management is the idea that adaptation strategies should be designed to be flexible and that the strength of adaptation strategies can be increased over time when needed, especially in light of uncertainty in future climate change projections. For instance, the near-term adaptation strategy for a culvert may consist of increased proactive maintenance, while the long-term adaptation strategy may include the addition of a structural adjustment to the culvert. In the *TEACR Slope Stability*[85] study, VDOT first installed a "toe wall" anchored by soil nails at the bottom of a landslide to stabilize it, but they also have a plan in place to install further measures if needed. VDOT continues to monitor the conditions to determine if additional action is required.

The adaptive management approach reduces the upfront capital needs while not excluding the possibility of adding additional levels of protection to the asset at a future date. Sometimes a "trigger" can be predetermined in the facility management plan to help the agency determine when it is appropriate to add additional protection. This trigger would be based on the most recent climate change science and the projected time required to plan, design, finance, and construct a chosen adaptation option.

Phased adaptation strategies can be incorporated into an overall asset management strategy. Asset management plans 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 lifecycle of the assets at minimum practicable cost. Incorporating adaptation planning into asset management helps to ensure that adaptation is considered in a systematic manner alongside other needs for maintenance and repair. Adaptation could also be phased in

[85] Throughout this section, case studies are referred to by an abbreviated title. For a full list of the case studies referenced in this report and their complete titles (with hyperlinks), see Appendix A: List of Case Studies.

during regular rehabilitation, reconstruction, and replacement activities in order to reduce the costs. For example, an asset might not be immediately replaced with an adaptation alternative but the opportunity for adaptation implementation may occur when the asset reaches a certain age or condition or when it is scheduled for rehabilitation, reconstruction, or replacement.

The performance of the facility and regional climate trends should be monitored after the project is constructed. The effects of changing climate trends on the asset should be revisited and periodically assessed to determine if the asset's design standards are being exceeded. Such monitoring and periodic assessment can help indicate if it might be necessary to implement additional improvements, change design guidelines, and/or alter operation and maintenance practices. As indicated in the *TEACR Culvert* study, the change in wildfire potential under a changing climate is uncertain and continual monitoring can increase understanding of the trend of this climate-related impact. In the *GC2 Navigable Bridge* study, bridge clearance issues for the existing asset will only arise if the more extreme sea level rise scenarios actualize, and only in the long term. Therefore, it may make sense to hold off on implementation, incorporate the adaptation consideration into the facility management plan, and continue to monitor the rate of sea level rise.

8.2. Revisit the Analysis in the Future

It may be important to revisit the adaptation analysis and conclusions in the future for several reasons, including:

Land use or demographic changes may change the functional use of the asset. An asset that used to be essential to the functioning of a community may become less critical if there are shifts in land use or population away from the area or new alternate routes are built. Conversely, a more minor asset could become more critical as the community grows and develops. As a result, the justification and need for an adaptation measure may shift. The relative costs and benefits of adaptation may change as well, requiring a revisit of the economic analysis.

For example, in *GC2 Bridge-Storm Surge*, the next significant storm surge event could eliminate the land uses on the low-lying causeway served by the study asset. If those land uses are not re-built, the need for the study asset would be lessened and adaptation of the asset may not be justified. On the other hand, land use changes can be part of longer-term adaptation options. In the *GC2 Navigable Bridge* case study, FHWA noted that land use planning and operational mechanisms could help address issues with navigational clearance due to sea level rise. Since navigational clearance is affected only in the long-term for that case study, it is possible to just plan on only having smaller vessels travel upriver. Companies that need access to larger ships may need to eventually relocate down river, or adjust their operations to accommodate service by smaller vessels.

Climate projection data, including sea level rise projections, will improve over time. Assumptions about how the asset will be exposed to climate change stressors could change as information improves. However, analyses conducted with existing climate information are still incredibly useful and insightful. Implementation of lower-cost adaptation measures can occur in the near-term with ongoing monitoring of new climate projections and modeling, as described in Section 8.1.

Advancements in engineering may make new adaptation measures feasible or lower the costs of others. Therefore, the range of potential adaptation solutions and the relative cost-effectiveness of the measures may change over time.

9. Ongoing FHWA Research

FHWA is continuing its research on incorporating climate change considerations into transportation projects beyond the case studies reviewed in this report. This chapter summarizes ongoing research.

These projects provide an opportunity to fill existing gaps, investigate topics in greater depth, and integrate information on new practices and data as they become available. The projects will help FHWA continue to update existing technical manuals (e.g., HEC-17,[86] HEC-25 Vol 2[87]) and tools (e.g., CMIP Climate Data Processing Tool[88]) as practices and data evolve.

Information and results of these projects will be posted on FHWA's Hydraulics Climate Change and Extreme Events Website and Sustainable Transportation and Resilience website.

The table below lists major projects of interest along with project collaborators. Each project is described further below the table.

Table 23: Ongoing FHWA Research Projects.

Study	Collaborator	Estimated Completion
Updating Precipitation Frequency Estimates under Non-Stationary Climate Conditions	National Weather Service (NWS)	2019
Flood Frequency Estimation for Hydrologic Design under Changing Conditions	U.S. Geological Survey (USGS)	2021
Potential Impact of Climate Change on U.S. Precipitation Frequency Estimates		2017
Climate Change Effects on Stream Geomorphology—the Maple River Stream Instability Study		2018
Sensitivity of Drainage Infrastructure to Climate Change	National Park Service (NPS)	2017
NCHRP 15-61: Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure	National Cooperative Highway Research Program (NCHRP)	2018
Geohazards, Extreme Events, and Climate Change		2019
Hurricane Sandy Follow-up and Vulnerability Assessment and Adaptation Analysis		2017

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86 FHWA, 2016b.
87 FHWA, 2014.
88 USDOT, 2016.

Study	Collaborator	Estimated Completion
Global Benchmarking Report		2017
Green Infrastructure Techniques for Coastal Highway Resilience		2018
Collaboration on Climate Resilience Under Bilateral Agreement	Rijkswaterstaat (RWS)	2018

Updating Precipitation Frequency Estimates under Non-Stationary Climate Conditions. Through this project, NWS and FHWA will attempt to address the potential impact of non-stationary climate on precipitation frequency estimates, such as those published in NOAA Atlas 14.[89] The project's primary objective is to develop a modeling framework that allows practitioners to integrate non-stationary climate effects into methodologies used to calculate precipitation frequency estimates; these methodologies are intended to be applicable at a national scale and to produce credible precipitation frequency estimates that Federal water agencies can rely on. NWS and FHWA will then use the resulting modeling framework to derive non-stationary precipitation frequency estimates for a pilot project and to determine precipitation frequency estimates for durations of five minutes through 60 days, at average recurrence intervals of one year through 1,000 years, at 30-arc seconds resolution (less than 1 km x 1 km; varies with latitude) for five northwestern states (ID, MT, OR, WA, WY). Ultimately, users will have the option to include climate change in the estimates.

Flood Frequency Estimation for Hydrologic Design under Changing Conditions. Through this project, USGS and FHWA will assess potential future changes to climate, land cover, snowpack, and agricultural and land drainage practices across the United States and the validity of assuming stationarity in the observed peak flow record. It is still largely unknown how ongoing and future changes to the variables mentioned above may translate to changes in flood frequency and magnitude, and how these changes challenge the current methodology for obtaining flood-frequency estimates. To fill these gaps, USGS and FHWA will identify rivers where trends in peak flows are present, diagnose and attribute changes in their flood frequencies (e.g., to changes in climate, land cover, snowpack, and agricultural and land drainage practices), and adjust flood-frequency analysis for observed and projected change. USGS and FHWA will use results of the study to develop code to provide a consistent framework for the analysis of trend detection, prepare national data sets, and run an analysis to determine regions for further analysis. The project sponsors will also explore approaches to estimating adjusted flood frequency at 163 un-gaged sites.

[89] NOAA, 2017b.

Potential Impact of Climate Change on U.S. Precipitation Frequency Estimates. Through this study, FHWA will conduct a historical trend analysis on the number of exceedances of precipitation frequency thresholds for different U.S. regions, building on previous work by the NWS Office of Hydrologic Development. FHWA will also survey state-of-the-art techniques for examining and expressing trends in precipitation depth or intensity. Then, FHWA will conduct pilot projects to examine the viability of different approaches for use in a comprehensive analysis that could be performed for the entire United States to produce credible results for use by Federal water agencies.

Climate Change Effects on Stream Geomorphology—the Maple River Stream Instability Study. The objective of this analysis is to evaluate potential future channel instability of the Maple River as it relates to Iowa Route 175 near Danbury given historic instability and potential climate change impacts. The Maple River is a laterally active channel flowing through agricultural land that has migrated several hundred feet in recent decades and is currently within approximately 100 feet of the Highway 175 ROW. FHWA will evaluate channel instability and near-term potential future channel change through a variety of approaches, including standard geomorphic methods, 2-D modeling, and computational fluid dynamics modeling, and then apply potential climate conditions to determine whether and to what degree climate conditions could affect channel instability in this area.

Sensitivity of Drainage Infrastructure to Climate Change. Through this study, FHWA will conduct a hydraulic analysis of the impact of increased precipitation on the performance of various classes of highway drainage infrastructure in riverine environments. Projected increases and changes in precipitation patterns may put highway drainage infrastructure at risk. However, the magnitude of projected increased precipitation is uncertain and each piece of drainage infrastructure may have a unique degree of resilience already built into its design. To quantify this resilience, FHWA will conduct a sensitivity analysis of drainage infrastructure components such as bridges, culverts, storm sewers, pavement inlets, gutters, and ditches in small, well-documented, relatively undeveloped watersheds (in national parks) that are projected to experience increased precipitation due to climate change. FHWA will study multiple current and future precipitation scenarios to determine the level of existing resilience and capacity of drainage infrastructure, as well as if the infrastructure currently meets today's design criteria. FHWA will also examine flow-induced "failures" (such as roadway overtopping) beyond design criteria. For each scenario, FHWA will determine which pieces of infrastructure and types of drainage infrastructure are most vulnerable. This information may help owners re-prioritize future investments in drainage infrastructure.

NCHRP 15-61: Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure. The objective of this study is to develop a national design guide to provide hydraulic engineers with the tools needed to adjust practices to account for climate change. The resulting design guide can serve as a basis for updates to AASHTO's Drainage Manual. NCHRP intends the project to be a collaborative effort among climate scientists, hydrologists, and highway hydraulic engineers. Through the study, NCHRP will quantitatively examine levels of robustness in existing hydraulic design practices, accounting for current levels of uncertainty, safety factors, conservative assumptions, and techniques that may allow transportation infrastructure to continue to function satisfactorily in a changing climate. NCHRP will also develop strategies to align the outputs of climate change science with the inputs needed by hydrologists and hydraulic engineers.

Geohazards, Extreme Events, and Climate Change. Through this project, FHWA will provide guidance to state DOTs and transportation agencies in their efforts to develop or improve their geohazards programs. Extreme events are a common trigger for geohazard events and, at any given location, a changing climate can affect the recurrence of these events in some way. FHWA has found little research to better understand and characterize these effects and their link with geohazards. Through this project, FHWA will provide guidance to transportation agencies on identifying and evaluating the severity, frequency, and intensity of geohazards; the interrelationship of geohazards with extreme events, antecedent conditions, and climate change; and mitigation strategies to avoid or reduce negative impacts to highway transportation infrastructure assets. FHWA will also provide climate change adaptation methods and processes to increase resilience in the design and performance management of highway transportation infrastructure.

Hurricane Sandy Follow-up and Vulnerability Assessment and Adaptation Analysis. FHWA is collaborating with partners in Connecticut, New Jersey, and New York to analyze the damage and disruption caused by Hurricane Sandy and other recent storms on the region's transportation systems. FHWA and their partners are leveraging the lessons learned from these events, as well as future climate and sea level rise projections, to develop feasible, cost-effective strategies to reduce and manage the risks of extreme weather events and climate change. The region's transportation agencies selected 10 regionally significant transportation facilities—including roads, bridges, tunnels, and ports—for a more detailed, engineering-based assessment of adaptation options. Results from the engineering assessments will inform a multimodal transportation vulnerability and risk assessment for the region. The results of the project will provide information to agencies in the tri-state region, and nationwide, seeking to plan and invest for long-term climate resilience while addressing today's transportation challenges.

Global Benchmarking Report. In this report, FHWA summarizes best practices and key findings from site visits to Denmark, the Netherlands, and Norway to meet with officials and learn first-hand about international best practices to integrate climate resilience concerns into highway planning and engineering. The sites include several locations where practitioners have implemented climate adaptation and climate resilience activities that yielded demonstrable results.

Green Infrastructure Techniques for Coastal Highway Resilience. In this project, FHWA seeks to improve the resilience of coastal roads, bridges, and highways through the implementation of ecosystem-based green infrastructure approaches. FHWA will investigate techniques that practitioners could implement as part of transportation planning, maintenance, and construction to preserve and/or improve natural infrastructure function, thereby increasing the resilience of highways to the effects of storm surge and sea level rise. The project includes five pilots along the Atlantic, Gulf, and Pacific coasts that are examining resilience strategies such as wave-tripping vegetated berms, living shorelines of various types, and dynamic revetments (cobble beaches). As a result of the project, FHWA will develop an implementation guide that provides information and analysis on green infrastructure techniques, climate adaptation and coastal resilience benefits and risks, co-benefits, costs (including ongoing maintenance costs), feasibility, and implementation considerations.

Collaboration on Climate Resilience Under Bilateral Agreement. Through this project, FHWA and Rijkswaterstaat (RWS) will test climate change resilience tools developed in both countries on two infrastructure projects. The Netherlands project is the A58 project, which expands a roadway in southern Holland from two lanes in each direction to three lanes in each direction. The U.S. project is the SR167 completion project, which completes a critical missing link to I-5 near Tacoma, Washington, including approximately 6 miles of new construction and five new interchanges. FHWA and RWS will test tools including ROADAPT[90] (a climate change adaptation framework and accompanying tools developed in Europe), the FHWA Climate Change and Extreme Weather Vulnerability Assessment Framework, and FHWA's Vulnerability Assessment Tool (VAST). Under the bilateral agreement, both sides are also sharing information on methods for analyzing changes in precipitation intensity and nature-based flood protection strategies.

[90] Deltares, 2017.

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Appendix A: List of Case Studies

This appendix provides a table with the full list of case studies referenced throughout this report. The table includes the full case study name, information on which project the case study was funded through, and the short project name, which is how the case study is referred to throughout this report, and a hyperlink to the study (if available).[91]

Table 24: List of Full and Abbreviated Case Study Names.

Project	Full Name	Short Name (used throughout report)
Gulf Coast Phase 2	Culvert Exposure to Precipitation Changes – The Airport Boulevard Culvert over Montlimar Creek	*GC2 Culvert*
Gulf Coast Phase 2	Bridge Over Navigable Waterway Exposure to Sea Level Rise – The Cochrane-Africatown USA Bridge	*GC2 Navigable Bridge*
Gulf Coast Phase 2	Continuous Welded Rail Exposure to Temperature Changes	*GC2 Rail*
Gulf Coast Phase 2	Road Alignment Exposure to Storm Surge – I-10 (Mileposts 24 and 25)	*GC2 Highway Surge*
Gulf Coast Phase 2	Coastal Tunnel Exposure to Storm Surge – The I-10 (Wallace) Tunnel	*GC2 Tunnel*
Gulf Coast Phase 2	Shipping Pier Exposure to Storm Surge – Dock One at the McDuffie Coal Terminal	*GC2 Coal Terminal*
Gulf Coast Phase 2	Pavement Mix Design Exposure to Temperature Changes	*GC2 Pavement*
Gulf Coast Phase 2	Operations and Maintenance (O&M) Activity Exposure to Climate Change and Extreme Weather Events	*GC2 O&M*
Gulf Coast Phase 2	Bridge Segment Exposure to Storm Surge – The US 90/98 Ramp to I-10 Eastbound at Exit 30	*GC2 Bridge-Storm Surge*
Gulf Coast Phase 2	Bridge Abutment Exposure to Storm Surge – US 90/98 Tensaw-Spanish River Bridge (Western Abutment)	*GC2 Bridge Approach-Storm Surge*

[91] At the time of publication, the Sandy Recovery case studies were not yet available online. When complete, the case studies will be published on FHWA's website at: https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/hurricane_sandy/
Likewise, the *TEACR Culvert* and *TEACR Permafrost Thaw* were not available online at the time of publishing. They will be made available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/index.cfm

Project	Full Name	Short Name (used throughout report)
Gulf Coast Phase 2	Bridge Approach Embankment Exposure to Sea Level Rise – US 90/98 Tensaw-Spanish River Bridge (Western Approach)	*GC2 Bridge Embankment-SLR*
Pilots Phase 1	Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure	*NJDOT Pilot*
Pilots Phase 2	Arizona Department of Transportation's Extreme Weather Vulnerability Assessment	*ADOT Pilot*
Pilots Phase 2	California Department of Transportation's District 1 Climate Change Vulnerability Assessment and Pilot Studies: FHWA Climate Resilience Pilot Final Report	*Caltrans Pilot*
Pilots Phase 2	Capital Area Metropolitan Planning Organization's Central Texas Extreme Weather and Climate Change Vulnerability Assessment of Regional Transportation Infrastructure	*CAMPO Pilot*
Pilots Phase 2	Connecticut Department of Transportation Climate Change and Extreme Weather Vulnerability Pilot Project	*CT DOT Pilot*
Pilots Phase 2	Hillsborough County Metropolitan Planning Organization (MPO): Vulnerability Assessment and Adaptation Pilot Project	*Hillsborough MPO Pilot*
Pilots Phase 2	Iowa Department of Transportation's Bridge and Highway Climate Change and Extreme Weather Vulnerability Assessment Pilot	*IDOT Pilot*
Pilots Phase 2	Integrating Storm Surge and Sea Level Rise Vulnerability Assessments and Criticality Analyses into Asset Management at Maine Department of Transportation	*MaineDOT Pilot*
Pilots Phase 2	Maryland State Highway Administration Climate Change Adaptation Plan with Detailed Vulnerability Assessment	*MDSHA Pilot*
Pilots Phase 2	Massachusetts Department of Transportation's Climate Change and Extreme Weather Vulnerability Assessments and Adaptation Options for the Central Artery	*MassDOT Pilot*
Pilots Phase 2	Metropolitan Transportation Commission's Climate Change and Extreme Weather Adaptation Options for Transportation Assets in The Bay Area Pilot Project	*MTC Pilot*

Project	Full Name	Short Name (used throughout report)
Pilots Phase 2	Michigan Department of Transportation Climate Vulnerability Assessment Pilot Project	*MDOT Pilot*
Pilots Phase 2	Minnesota Department of Transportation Flash Flood Vulnerability and Adaptation Assessment Pilot Project	*MnDOT Pilot*
Pilots Phase 2	New York State Department of Transportation's Climate Vulnerability and Economic Assessment for At-Risk Transportation Infrastructure in the Lake Champlain Basin, New York	*NYSDOT Pilot*
Pilots Phase 2	North Central Texas Council of Government's Climate Change/Extreme Weather Vulnerability and Risk Assessment for Transportation Infrastructure in Dallas and Tarrant Counties	*NCTCOG Pilot*
Pilots Phase 2	Oregon Department of Transportation's Climate Change Vulnerability Assessment and Adaptation Options Study	*ODOT Pilot*
Pilots Phase 2	South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project	*South Florida Pilot*
Pilots Phase 2	Tennessee Department of Transportation's Assessing the Vulnerability of Tennessee Transportation Assets to Extreme Weather	*TDOT Pilot*
Pilots Phase 2	Washington State Department of Transportation's Creating a Resilient Transportation Network in Skagit County: Using Flood Studies to Inform Transportation Asset Management	*WSDOT Pilot*
Pilots Phase 2	Western Federal Lands Highway Division/Alaska Department of Transportation and Public Facilities	*WFLHD/AKDOT&PF Pilot*
Sandy Recovery	Bergen Avenue, West Babylon, NY (Suffolk County, NYMTC)	*Sandy: Bergen Avenue, NY*
Sandy Recovery	Governor's Island Ventilation Building, The Hugh L. Carey Tunnel (I-478), New York NY	*Sandy: Governor's Island Ventilation Building*
Sandy Recovery	Long Beach Road/Austin Boulevard Corridor, Town of Hempstead, NY (Nassau County/MYMTC)	*Sandy: Long Beach Road, NY*
Sandy Recovery	Loop Parkway Bridge Over Long Creek, Town of Hempstead, NY (Nassau County, NYMTC)	*Sandy: Loop Parkway Bridge*
Sandy Recovery	Metro-North Railroad New Haven Line Track and Power Infrastructure, Pelham, NY (MTA)	*Sandy: Metro-North Railroad*
Sandy Recovery	NJ Route 7, Kearny, NJ	*Sandy: NJ Route 7*

Project	Full Name	Short Name (used throughout report)
Sandy Recovery	PANYNJ Port Jersey Marine Terminal, Peninsula at Bayonne Harbor, Bayonne, NJ (Hudson County/NJTPA)	*Sandy: Port Jersey Marine Terminal*
Sandy Recovery	Thomas A. Mathis Bridge (EB NJ 37), Toms River/Seaside Heights, NJ (Ocean County)	*Sandy: Thomas A. Mathis Bridge*
Sandy Recovery	Yellow Mill Drawbridge, (CT 130 Over Yellow Mill Channel), Bridgeport, CT (CTDOT)	*Sandy: Yellow Mill Drawbridge*
TEACR Case Studies	Sea Level Rise and Storm Surge Impacts on a Coastal Bridge: I-10 Bayway, Mobile Bay, Alabama	*TEACR Coastal Bridge*
TEACR Case Studies	Living Shoreline along Coastal Roadways Exposed to Sea Level Rise: Shore Road in Brookhaven, New York	*TEACR Living Shoreline*
TEACR Case Studies	Temperature and Precipitation Impacts on Cold Region Pavement: State Route 6/State Route 15/State Route 16 in Maine	*TEACR Pavement Freeze-Thaw*
TEACR Case Studies	Comparison of Economic Analysis Methodologies and Assumptions: Dyke Bridge in Machias, Maine	*TEACR Economic Assessments*
TEACR Case Studies	Temperature and Precipitation Impacts to Pavements on Expansive Soils: Proposed State Highway 170 in North Texas	*TEACR Pavement Shrink-Swell*
TEACR Case Studies	Precipitation and Temperature Impacts on Rock and Soil Slope Stability: Interstate I-77 in Carroll County, Virginia	*TEACR Slope Stability*
TEACR Case Studies	Barrier Island Roadway Overwashing from Sea Level Rise and Storm Surge: US 98 on Okaloosa Island, Florida	*TEACR Roadway Surge*
TEACR Case Studies	Incorporating Climate Change into the Design of Roadways Built on Permafrost	*TEACR Permafrost Thaw*
TEACR Case Studies	Wildfire and Precipitation Impacts on a Culvert: US 34 at Canyon Cove Lane, Colorado	*TEACR Culvert*

Appendix B: Table of Derived Climate Variables

This table provides a summary of the derived climate change variables used in the various FHWA case studies. The last row of the table indicates whether or not the variable is included in the US DOT CMIP Climate Data Processing Tool.

TABLE 25: DERIVED CLIMATE VARIABLES, PURPOSE, AND SOURCES.

Climate Change Variable	Derived Variable	Purpose of Derived Variable	Case Studies	Included in CMIP Tool?
Temperature	Annual maximum temperature (hottest day of the year)	To evaluate extreme heat impacts on the electrical and mechanical components of a bridge, on rail infrastructure, and on construction windows.	*TEACR Pavement Freeze-Thaw* *TEACR Pavement Shrink-Swell* *Sandy: Loop Parkway Bridge* *Sandy: Metro-North Railroad* *Gulf Coast 2 (GC2) Rail* *ADOT Pilot*	✓
	Annual minimum temperature (coldest day of the year)	To help estimate freeze-thaw conditions or evaluation potential of materials to shrink and swell.	*TEACR Pavement Freeze-Thaw* *TEACR Pavement Shrink-Swell* *GC2 Pavement* *GC2 Rail*	✓
	Annual average temperature	To evaluate changes in temperature on transportation infrastructure.	*TEACR Pavement Freeze-Thaw* *TEACR Pavement Shrink-Swell* *Sandy: Metro-North Railroad* *CAMPO Pilot* *MDSHA Pilot* *MDOT Pilot* *NCTCOG Pilot*	✓

Climate Change Variable	Derived Variable	Purpose of Derived Variable	Case Studies	Included in CMIP Tool?
	Average daily maximum temperature	To evaluate: extreme heat impacts on pavement deformation, thermal expansion, and worker safety; increasing temperature impacts on roads; impacts to permafrost formation and thawing.	*ADOT Pilot* *Caltrans Pilot* *WFLHD/AKDOT&PF Pilot*	
	Average daily minimum temperature	To evaluate changes in minimum temperature impacts to transportation infrastructure	*ADOT Pilot*	
	Monthly average temperature	To evaluate temperature impacts on transportation infrastructure, impacts to permafrost formation and thawing.	*TEACR Pavement Freeze-Thaw* *NCTCOG Pilot* *TDOT Pilot* *WFLHD/AKDOT&PF Pilot*	
	Seasonal average temperature	To evaluate changes in seasonal temperature on roads (i.e., freeze/thaw cycles), and seasonal changes in extreme temperature on transportation infrastructure.	*CAMPO Pilot* *MDSHA Pilot* *MDOT Pilot* *NCTCOG Pilot*	✓[a]
	Ambient air temperature	To evaluate impacts of permafrost formation and thawing to transportation assets	*WFLHD/AKDOT&PF Pilot*	
	Length of freezing season (number of days below freezing)	To evaluate freezing temperature impacts on frost heaves, winter maintenance, and construction windows	*TEACR Pavement Freeze-Thaw* *ADOT Pilot*	✓
	Average number of freezing days per month	To help understand freeze-thaw impacts on pavements	*TEACR Pavement Freeze-Thaw*	

Climate Change Variable	Derived Variable	Purpose of Derived Variable	Case Studies	Included in CMIP Tool?
	Annual average degree days (the sum of the differential between a selected temperature and the highest or lowest temperature of the day; summed over all the days of the year) Includes: Annual freezing index (degree days below 32°F); annual thawing index (degree days above 32°F)	To understand freeze-thaw, expansion and contraction issues, and potential for permafrost thaw.	*TEACR Pavement Freeze-Thaw* *TEACR Pavement Shrink-Swell* *TEACR Permafrost Thaw*	
	Number of days where the minimum daily temperature was below 32°F and the daily maximum temperature was above 32°F	To understand impacts of freeze-thaw events on transportation assets and slope stability.	*TEACR Slope Stability*	✓
	Number of days greater than 90°F, 95°F, or 100°F.	To evaluate extreme heat impacts on pavement deformation, thermal expansion, worker safety, and other heat impacts on transportation infrastructure	*MDSHA Pilot* *Caltrans Pilot* *MDOT Pilot* *ADOT Pilot* *CAMPO Pilot* *ODOT Pilot*	✓[b]
	Annual consecutive 100°F days	To evaluate extreme heat impacts on transportation infrastructure	*NCTCOG Pilot*	✓

Climate Change Variable	Derived Variable	Purpose of Derived Variable	Case Studies	Included in CMIP Tool?
	Three-day average maximum temperatures (hottest three consecutive days)	To evaluate extreme heat impacts on the electrical and mechanical components of a bridge, and extreme heat impacts on rail infrastructure.	*Sandy: Loop Parkway Bridge* *Sandy: Metro-North Railroad*	✓[c]
	Urban Heat Island	To evaluate changes in urban heat island and subsequent extreme heat impacts on transportation infrastructure.	*NCTCOG Pilot*	
	Maximum seven consecutive day average high air temperature	To measure extreme heat impacts on pavement deterioration, thermal misalignment, and maintenance and construction crew impacts	*GC2 Pavement* *CAMPO Pilot*	✓
	Annual average number of cold events (cold/wind chill and extreme cold/wind chill)	To evaluate extreme cold impacts on transportation infrastructure	*TDOT Pilot*	
	Annual average number of hot events (heat and excessive heat)	To evaluate extreme heat impacts on transportation infrastructure	*TDOT Pilot*	✓
Precipitation and drought	Annual average precipitation	To evaluate changes in precipitation on erosion, bridge scour, localized flooding, drought, overtopping, and corrosion impacts on transportation infrastructure (To evaluate changes in precipitation (drought and flood) on transportation infrastructure.	*TEACR Pavement Freeze-Thaw* *TEACR Pavement Shrink-Swell* *TEACR Slope Stability* *CAMPO Pilot* *MDSHA Pilot* *MDOT Pilot* *NCTCOG Pilot*	✓

Climate Change Variable	Derived Variable	Purpose of Derived Variable	Case Studies	Included in CMIP Tool?
	Total annual precipitation	To evaluate the potential impacts of flooding on transportation infrastructure, and the relationship between total precipitation and rain/snow related crashes or transit delays	*Caltrans Pilot* *NCTCOG Pilot*	
	Monthly average precipitation		*TEACR Pavement Freeze-Thaw*	✓
	Monthly total precipitation	To evaluate precipitation impacts on transportation infrastructure	*TDOT Pilot*	
	Maximum one-day precipitation	To evaluate extreme precipitation impacts on highway infrastructure	*ODOT Pilot*	✓
	Maximum two-day precipitation	To evaluate extreme precipitation impacts on highway infrastructure	*ODOT Pilot*	✓[d]
	Maximum five-day precipitation	To evaluate extreme precipitation impacts on highway infrastructure	*ODOT Pilot*	✓[d]

Climate Change Variable	Derived Variable	Purpose of Derived Variable	Case Studies	Included in CMIP Tool?
	24-hour precipitation depths by percentile (95th, 98th, 99th) or return period (2-, 5-, 10-, 25-, 50-, 100-, 500-year storms)	To evaluate extreme precipitation impacts on the drainage system of a roadway; extreme rainfall intensity on transportation infrastructure; extreme precipitation impacts on bridge scour, roadway and bridge overtopping, and corrosion impacts on transportation infrastructure; and flash flooding risks to the highway system.	*TEACR Culvert (+500 year storm)* *TEACR Slope Stability* *Sandy: Long Beach Road, NY* *Sandy: Governor's Island Ventilation Building (only 100- and 500-year storms)* *GC2 Culvert* *Caltrans Pilot* *CAMPO Pilot* *CT DOT Pilot* *MDSHA Pilot* *MnDOT Pilot* *NYSDOT Pilot*	✓[e]
	Annual seasonal precipitation	To evaluate extreme precipitation impacts on flooding, washouts, erosion, bridge scour, and mudslides, overtopping, and corrosion.	*TEACR Pavement Shrink-Swell* *TEACR Slope Stability* *ADOT Pilot* *MDSHA Pilot* *NCTCOG Pilot*	
	Average seasonal precipitation	To evaluate changes in seasonal precipitation on erosion, bridge scour, overtopping, corrosion, localized flooding, and wildfire risk.	*ADOT Pilot* *CAMPO Pilot* *MDSHA Pilot* *MDOT Pilot* *ODOT Pilot*	✓

Climate Change Variable	Derived Variable	Purpose of Derived Variable	Case Studies	Included in CMIP Tool?
	Storm precipitation	To evaluate extreme precipitation impacts on the drainage system of a roadway; on erosion, bridge scour, overtopping, corrosion, localized flooding	*TEACR Slope Stability* *Sandy: Long Beach Road, NY* *ADOT Pilot* *Hillsborough MPO Pilot* *MDSHA Pilot* *MDOT Pilot* *South Florida Pilot* *WSDOT Pilot*	✓[f]
	Average number of baseline extreme rainfall events per year	To evaluate extreme precipitation impacts on scour, overtopping, and corrosion impacts on transportation infrastructure	*MDSHA Pilot*	✓
	Annual average number of hydrologic events (heavy rain, flash flood, flood)	To evaluate the frequency of extreme precipitation impacts on transportation infrastructure	*TDOT Pilot*	✓[f]
	Annual average number of hail events	To evaluate the frequency of hail impacts on transportation infrastructure	*TDOT Pilot*	
	Annual average number of drought events	To evaluate the frequency of drought impacts on transportation infrastructure	*TDOT Pilot*	
	Annual average of winter events (winter weather, sleet, freezing fog, frost freeze, heavy snow, winter storm, ice storm)	To evaluate the frequency of winter weather impacts on transportation infrastructure	*TDOT Pilot*	

Climate Change Variable	Derived Variable	Purpose of Derived Variable	Case Studies	Included in CMIP Tool?
	Largest three-day rainfall event per season	To evaluate extreme precipitation impacts on scour, overtopping, and corrosion impacts on transportation infrastructure (MDSHA Pilot).	*MDSHA Pilot*	✓
	Peak flow for 2-, 5-, 10-, 25-, 50-, 100-, 500-year rainfall	To evaluate extreme precipitation impacts on the drainage system of a roadway; flooding impacts on highway structures and roadway embankments; flash flooding risks to the highway system; the extent, depth, and pathways of inundation events	*Sandy: Long Beach Road, NY* *GC2 Culvert (peak flow)* *CT DOT Pilot* *IDOT Pilot* *MTC Pilot* *MnDOT Pilot* *NYSDOT*	
	Palmer Drought Severity Index	To evaluate drought and the correlation with Urban Heat Island	*NCTCOG Pilot*	
	Annual average dry days (<0.01 in.)	To evaluate drought	*CAMPO Pilot*	
	Keetch-Byram Drought Index (KBDI)	To help characterize future wildfire scenarios	*TEACR Culvert*	

Climate Change Variable	Derived Variable	Purpose of Derived Variable	Case Studies	Included in CMIP Tool?
Sea level rise and storm surge	Projected sea level rise elevations	To evaluate storm sea level rise and flooding impacts on port terminal infrastructure and electrical components; the drainage system of a roadway; structural, electrical, and mechanical components of a bridge.	*TEACR Roadway Surge* *TEACR Coastal Bridge* *TEACR Economic Assessments* *TEACR Living Shoreline* *Sandy: Port Jersey Marine Terminal* *Sandy: Long Beach Road, NY* *Sandy: Loop Parkway Bridge* *Sandy: Thomas A. Mathis Bridge* *Sandy: Bergen Avenue, NY* *Sandy: Governor's Island Ventilation Building* *Sandy: NJ Route 7* *Sandy: Yellow Mill Drawbridge* *GC2 Navigable Bridge* *GC2 Bridge Embankment-SLR* *Caltrans Pilot* *Hillsborough MPO Pilot* *Maine DOT Pilot* *MassDOT Pilot* *MDSHA Pilot* *MTC Pilot* *ODOT Pilot* *South Florida Pilot*	

Climate Change Variable	Derived Variable	Purpose of Derived Variable	Case Studies	Included in CMIP Tool?
	Storm surge elevation	To evaluate storm surge elevation and flooding impacts on port terminal infrastructure and electrical components; drainage system of a roadway; structural, electrical and mechanical components of a bridge.	*TEACR Roadway Surge* *TEACR Coastal Bridge* *TEACR Economic Assessments* *TEACR Living Shoreline* *Sandy: Port Jersey Marine Terminal* *Sandy: Long Beach Road, NY* *Sandy: Loop Parkway Bridge* *Sandy: Thomas A. Mathis Bridge* *Sandy: Bergen Avenue, NY* *Sandy: NJ Route 7* *Sandy: Yellow Mill Drawbridge* *GC2 Bridge Approach-Storm Surge* *GC2 Bridge-Storm Surge* *GC2 Highway Surge* *GC2 Tunnel* *GC2 Coal Terminal* *Hillsborough MPO Pilot* *Maine DOT Pilot* *MassDOT* *MDSHA Pilot* *WFLHD/AKDOT&PF Pilot*	

Climate Change Variable	Derived Variable	Purpose of Derived Variable	Case Studies	Included in CMIP Tool?
	Wave height	To evaluate wave height impacts on coastal airport infrastructure	*TEACR Coastal Bridge* *GC2 Bridge Embankment-SLR (depth-limited wave height)* *WFLHD/AKDOT&PF Pilot*	
	Storm surge inundation depth	To help characterize depth of inundation at particular locations.	*TEACR Coastal Bridge*	
Wildfire	Keetch-Byram Drought Index (KBDI)	To help characterize future wildfire scenarios	*TEACR Culvert*	
	Annual number of days with chance of wildfire	To help characterize future wildfire scenarios	*TEACR Culvert*	
	Projected fire risk	To evaluate wildfire risk to transportation infrastructure (Caltrans Pilot).	*Caltrans Pilot*	
	Wildfire exposure rating curves	To evaluate wildfire risk to transportation infrastructure (Caltrans Pilot).	*Caltrans Pilot*	
Other	Maximum depth of frost penetration	To help understand freeze-thaw cycles at certain vertical points in a roadway	*TEACR Pavement Freeze-Thaw*	
	Design pavement low temperatures	To understand potential impacts of freeze-thaw cycles on pavement	*TEACR Pavement Freeze-Thaw*	
	Annual average potential ice days (≤ 32°F and > 0.01 in. precipitation)	To measure extreme cold and icing impacts on pavements	*CAMPO Pilot*	

Climate Change Variable	Derived Variable	Purpose of Derived Variable	Case Studies	Included in CMIP Tool?
	Annual average number of wind events (strong wind, high wind, thunderstorm wind) by county	To evaluate the frequency of wind event impacts on transportation infrastructure	*TDOT Pilot*	
	Daily average wind speed	To evaluate wind speed impacts on wave height and surge	*WFLHD/AKDOT&PF Pilot*	
	Annual average number of twister events (funnel cloud, dust devil, tornado)	To evaluate the frequency of twister event impacts on transportation infrastructure	*TDOT Pilot*	
	Annual average number of lightning events	To evaluate the frequency of lightning event impacts on transportation infrastructure	*TDOT Pilot*	
	Daily maximum runoff	To evaluate extreme runoff impacts to transportation infrastructure	*Caltrans Pilot*	
	Total annual runoff	To evaluate extreme runoff impacts to transportation infrastructure	*Caltrans Pilot*	
	Sea ice extent	To evaluate sea ice impacts on surge	*WFLHD/AKDOT&PF Pilot*	
	Landslide risk	To evaluate landslide risk to transportation infrastructure	*Caltrans Pilot*	
	Landslide events (10-, 100-, 1,000-, 10,000-, 50,000 cubic yards)	To evaluate landslide risk associated with permafrost thaw and increased precipitation on a road	*WFLHD/AKDOT&PF Pilot*	
	Mean annual relative humidity	To understand shrink-swell implications of climate change on local soils	*TEACR Pavement Shrink-Swell*	

Climate Change Variable	Derived Variable	Purpose of Derived Variable	Case Studies	Included in CMIP Tool?
	Annual soil moisture	To evaluate soil moisture impacts on soil plasticity, drought, and wildfire sensitivity	*CAMPO Pilot*	
	Seasonal soil moisture	To evaluate soil moisture impacts on soil plasticity, drought, and wildfire sensitivity	*CAMPO Pilot* *NCTCOG Pilot*	
	Thornthwaite Moisture Index (humidity/aridity of soil)	To understand shrink-swell implications of climate change on local soils	*TEACR Pavement Freeze-Thaw* *TEACR Pavement Shrink-Swell*	

a) The CMIP Climate Data Processing Tool calculates the highest four-day average summer temperatures.

b) The CMIP Climate Data Processing Tool can calculate “Very Heavy” 24-hour precipitation amount, “Extremely Heavy” 24-hour precipitation amount, average number of baseline “Very Heavy” precipitation events per year, and average number of baseline “Extremely Heavy” precipitation events per year.

c) The CMIP Climate Data Processing Tool calculates average summer temperatures.

d) The CMIP Climate Data Processing Tool calculates average number of days per year above 95°F, 100°F, 105°F, or 110°F.

e) The CMIP Climate Data Processing Tool can calculate “Very Heavy” 24-hour precipitation amount and “Extremely Heavy” 24-hour precipitation amount.

f) The CMIP Climate Data Processing Tool can calculate the largest three-day precipitation event per season.

Appendix C: Compilation of Lessons Learned

This appendix includes a compilation of the various lessons learned tables and additional considerations found throughout the report.

Table 26 provides a summary of the overarching lessons learned. For more information, see Section 5.1.

TABLE 26: OVERARCHING LESSONS LEARNED

Lesson Category	Lessons Learned
Scoping Asset-Level Adaptation Assessments	Flexible approaches are best.
	Focus data collection on the most critical elements, utilizing readily available data.
Applying Climate Science and Managing Uncertainty	While engineers should alter the inputs to engineering analyses due to climate change, the applicable design standards should not be altered.
	The use of historic climate data in lieu of climate projections is sometimes appropriate, but historic data should always be as up to date as possible.
	Maintenance records from extreme weather events can help practitioners understand the likelihood of future infrastructure damage.
	Historical climate data may be useful for a first-cut assessment of relative vulnerability and to narrow the number of assets that require detailed analysis, but to incorporate non-stationarity into a design, climate modeling projections should be used.
	Climate projections developed specifically for the study region by qualified climate scientists/modelers can help account for unique considerations.
	Existing tools can translate climate model outputs into variables that are appropriate for engineering design.
	Practitioners can compare climate projections to historical/observed climate values to increase integrity of results.
	The range of possible future emissions and climate scenarios should be considered, rather than focusing on just one projected scenario.
	Increases in the frequency of smaller, nuisance events should be considered in addition to extreme weather events.
	Given climate uncertainty, taking an incremental approach to adaptation may help reduce the risk of overspending while still increasing resilience.
	To avoid misinterpretation, engineers need to understand differences in conflicting future precipitation climate narratives that may be generated by groups of various climate models.

Lesson Category	Lessons Learned
Integrating Climate and Weather Risks into Asset Management	Feeding information gathered and produced through engineering-informed adaptation studies into asset management programs may assist with more robust decision-making.
	Data generated from asset management systems may be leveraged to augment engineering-informed adaptation studies.
	Climate change and extreme weather event risks should be considered alongside other risks and agency priorities in asset management plans.
	Practitioners may want to consider the impact of future environmental conditions on deterioration rates when conducting lifecycle planning.
Breaking Down Silos	Coordination among agencies with a vested interest in infrastructure resilience limits incompatible initiatives.
	Dialogue and communication across disciplines helps discourage barriers when undertaking climate change studies.
Selecting and Implementing Adaptation Measures	It may be helpful to define failure and how it could occur before selecting an adaptation strategy.
	Existing infrastructure designed using current or older climate data sets may still have a level of resiliency under future climate conditions.
	Many climate adaptation measures will be amplified forms of countermeasures currently installed to manage risks associated with today's environmental conditions.
	When selecting adaptation measures, the remaining life of the facility is important to consider.
	An adaptation portfolio approach to risk mitigation is likely to result in a suite of potentially viable options.
	When conducting analyses and selecting adaptation measures, policy-makers should provide guidance on risk tolerance across assets.
	Ecosystem-based adaptation and non-structural solutions may provide similar protection but broader project benefits.
	Long-term strategic land use planning can be an alternative to modifying the transportation asset.
Understanding Conservatism in Design Assumptions	Multiple conservative assumptions can compound to produce an overly conservative result.
	Additional criteria routinely applied in designs may provide additional conservatism.
Considering the Bigger Picture	Regional or corridor-scale vulnerability and criticality screens bring focus to asset-level studies.

Lesson Category	Lessons Learned
	Sometimes the most appropriate adaptation measure can only be identified when considering the bigger picture.
	Avoid creating stranded assets or “adaptation islands.”
	An adaptation strategy at a broader geographic scale may be appropriate.
	When evaluating adaptation strategies, it is important to consider potential secondary impacts or cascading consequences of a failed asset.
	Potential impacts on adjacent property due to proposed construction conditions should be addressed when designing for adaptation in urbanized areas.
	Post-event assessments of damage mechanisms can provide information for enhancing resilience to extreme events.
	Marine vessels have lower adaptive capacity than road users to disruptions at coastal bridges.

Table 27 provides an overview of the coastal hydraulics lessons learned. For more information, see Section 5.3.3.

Table 27: Coastal Hydraulics Lessons Learned

Lesson Category	Lessons Learned
Impacts on Infrastructure	Sea level rise will progressively make coastal transportation more vulnerable and less functional.
	Different types of coastal structures are inherently more or less sensitive to sea level rise.
	Sea level rise may have already contributed to damage of one major U.S. bridge during a hurricane.
Conducting Vulnerability Assessments	The Saffir-Simpson hurricane category scale is not appropriate for many coastal vulnerability assessments.
	The effect of sea level rise on peak storm surge levels can be non-linear.
	Original modeling of storm surge and waves is appropriate for major coastal projects.
	All appropriate engineering disciplines are needed for assessments of coastal assets.
Developing Adaptation Measures	Coastal climate change adaptation measures will be similar to coastal engineering strategies for improving resilience to today’s extreme weather events.
	Many coastal climate adaptation measures may be economically justified today as resilience measures, and the economic justification will increase as sea levels rise.

	Countermeasures and retrofits commonly suggested for bridges vulnerable to coastal storms may not be effective.
	A "living shoreline" can be a suitable climate adaptation measure for roadway protection.

Table 28 provides an overview of the riverine flooding lessons learned. For more information, see Section 5.3.3.

TABLE 28: RIVERINE FLOODING LESSONS LEARNED

Lesson Category	Lessons Learned
Appropriate Use of Future Precipitation Projections	If climate models predict decreases in extreme event precipitation under future narratives, then current conditions will control project designs.
	The use of 24-hour duration precipitation projections from climate models are better suited for the analysis of larger watersheds.
Use of Historical Data in Adaptation Analyses	When evaluating infrastructure using historical precipitation data sets, engineers should consider a range of flow events beyond the standard design storm.
Use of Rainfall/Runoff Modeling in Climate Adaptation Studies	Rainfall/runoff models (as opposed to regression-based approaches) are better suited to incorporating future precipitation projections, but they require more detailed knowledge of corresponding rainfall patterns and the response of the watershed to those patterns over an extended period of time.
	In larger watersheds, peak storm flow response may not linearly follow trends in climate change precipitation as increases in peak flows may be more dependent on the watershed characteristics and dynamic response to precipitation than on an increase in precipitation alone.
Understanding the Resiliency of Existing Facilities	Hydraulic performance curves can help illustrate the existing resilience, or lack thereof, of an asset under various flow scenarios.
Wildfire Impacts and Adaptation	Wildfire burn of a watershed causes a dramatic increase to storm flows and creates the potential for debris flows.
	Due to the short time horizon of wildfire impairment to a watershed, the risk of occurrence of extreme storm flows is lowered; therefore lower design storm conditions may be appropriate for post-fire designs.
	Reactive adaptation of culverts to wildfires is economically justifiable due to the relatively low probability of wildfire occurrence combined with the high cost of culvert upsizing.

Lesson Category	Lessons Learned
	Wildfire debris flows threaten riverine infrastructure by bulking (increasing) storm flow rates and by increasing the risk of debris clogging/aggradation of the river channel.

Table 29 provides an overview of the pavement and soils lessons learned. For more information, see Section 5.4.3.

Table 29: Pavement and Soils Lessons Learned

Lesson Category	Lessons Learned
Impacts on Pavement	Changes in temperature and precipitation could have widespread impacts on pavement performance, resulting in significant adaptation costs.
	Temperature and moisture changes affect the entire pavement system.
	Pavement designers must account for climate uncertainty when assessing existing pavement systems and developing pavement mix designs.
	Climate change will affect seasonal truckload restriction policies.
	Although the current state of climate model data is not “plug-and-play” with current pavement design and analysis tools, practitioners can frequently develop workarounds.
Impacts on Landslides and Rock Falls	Detailed climate data are not necessary for an initial, general assessment of climate change impacts on soil stability.
	To determine if climate change will increase weathering, practitioners must consider projections of freeze-thaw cycle frequency, temperatures, and precipitation amount, as well as the relative timing of these events.
Impacts on Permafrost Thaw	Location-specific permafrost and soil data are critical.
	The warming associated with climate change may be too great to enable long-term prevention of permafrost thaw underneath a roadway.

Table 30 provides an overview of the mechanical and electrical lessons learned. For more information, see Section 5.5.2.

Table 30: Mechanical and Electrical Lessons Learned

Lesson Category	Lesson Learned
Flooding	Water could enter mechanical and electrical rooms through many entry paths.
	Visuals of sea level rise and storm surge scenarios overlaid on as-built drawings can help communicate exposure.

Lesson Category	Lesson Learned
Increased Temperatures	Key temperature thresholds can be selected using experience, professional judgment, and climate change scenarios.

Table 31 provides an overview of additional considerations for the selection of adaptation strategies. For more information, see Chapter 7.

Table 31: Additional Considerations

Focus Area	Additional Considerations
Environment	Adaptation measures may have effects on habitats and natural resources.
	Indicators may help quantify environmental impacts of adaptation measures.
Economy	Indicators of the asset's importance to the local economy can be used to understand the value of protecting the asset from climate change.
Society	Context-sensitive design can enhance the aesthetics and recreational uses of the project.
	Prioritize adaptation funding for assets that are vulnerable and serve emergency response services.
	Not adapting the transportation network can render disadvantaged populations more vulnerable to climate change.
	Implementation of adaptation measures can have negative impacts on disadvantaged populations.
Governance	Permit requirements may affect adaptation option development.
	Encroachments in regulatory floodplains and waters may require design modifications.
	Historic landmarks can be harder to modify for adaptation.
	Environmental permitting requirements for fish passage can affect the adaptation design.
	Variances may be needed to implement some adaptation strategies.
	Low risk tolerance and/or high pressure from the public for resilient infrastructure may contribute to the justification for funding adaptation.
	Liability concerns may limit an agency's ability to provide broader flood protection.
Systematic Considerations	The response of the surrounding natural environment to climate change may necessitate different adaptation strategies.
	Trends in vehicle traffic volumes have implications for adaptation planning.
	Criticality and redundancy in the transportation network are factors in adaptation investment.

Focus Area	Additional Considerations
Agency Priorities	Timing of capital funding availability for adaptation measures matters.
	Manage cumulative costs of adaptation across the system.
	Balance upfront costs of adaptation vs. costs of damages given no adaptation.
	Constructability and ROW issues are important for large adaptation projects.
	Consider the durability of adaptation strategies in the design of such measures.

Appendix D: Abbreviations and Glossary

Abbreviations

Abbreviation	Definition
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt concrete
ACE	Air convecting embankment
ADOT	Arizona Department of Transportation
AKDOT&PF	Alaska Department of Transportation and Public Facilities
ARI	Average recurrence intervals
AUC	Area under the curve
BCA	Benefit-cost analysis
BCR	Benefit-cost ratio
Caltrans	California Department of Transportation
CAMPO	Capital Area Metropolitan Planning Organization
CDOT	Colorado Department of Transportation
CFR	Code of Federal Regulations
CRCP	Continuously reinforced concrete pavement
CT DOT	Connecticut Department of Transportation
DOT	Department of Transportation
EIA	Economic impact analysis
EO	Executive Order
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FLMA	Federal Land Management Agencies
GC2	FHWA Gulf Coast Study, Phase 2
HEC	Hydraulic Engineering Circular
Hillsborough MPO	Hillsborough County Metropolitan Planning Organization
HVAC	Heating, ventilation, and air-conditioning.
IDF	Intensity-Duration-Frequency
IDOT	Iowa Department of Transportation
IMPLAN	Impact Analysis for Planning
IPCC	Intergovernmental Panel on Climate Change
ITS	Intelligent Transportation Systems
KBDI	Keetch-Byram Drought Index
LCCA	Lifecycle cost analysis
LTPPBind	Long Term Pavement Performance Bind
MaineDOT	Maine Department of Transportation

Abbreviation	Definition
MassDOT	Massachusetts Department of Transportation
MDOT	Michigan Department of Transportation
MDSHA	Maryland State Highway Administration
MnDOT	Minnesota Department of Transportation
MP	Mile Post
MPO	Metropolitan Planning Organization
MTA	New York Metropolitan Transportation Authority
MTC	Metropolitan Transportation Commission
NA-CORDEX	North American Coordinated Regional Climate Downscaling Experiment
NCHRP	National Cooperative Highway Research Program
NCTCOG	North Central Texas Council of Government
NEPA	National Environmental Policy Act
NJDOT	New Jersey Department of Transportation
NOAA	National Oceanic and Atmospheric Administration
NPV	Net present value
NWS	National Weather Service
NYSDOT	New York State Department of Transportation
O&M	Operations and maintenance
ODOT	Oregon Department of Transportation
RCP	Representative concentration pathway
REMI	Regional Economic Models Inc.
ROW	Right of way
RWS	Rijkswaterstaat
SEPA	State Environmental Protection Act
SFHA	Special Flood Hazard Areas
SRES	Special Report on Emissions Scenarios
SWAN	Simulating WAves Nearshore
TDOT	Tennessee Department of Transportation
TEACR	Transportation Engineering Approaches to Climate Resiliency
TRB	Transportation Research Board
USGS	U.S. Geological Survey
VAST	FHWA's Vulnerability Assessment Scoring Tool
VDOT	Virginia Department of Transportation
WFLHD	Western Federal Lands Highway Division
WSDOT	Washington State Department of Transportation

Glossary

Term	Definition	Source
AASHTOWare Pavement ME Design model	AASHTOWare Pavement ME Design is the next generation of pavement design software, which builds upon the National Cooperative Highway Research Program mechanistic-empirical pavement design guide.	
Acute climate stressors	Short-lived, sporadic events such as floods or storm events.	
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.	EO 5520
Adaptation Decision-making Assessment Process (ADAP)	A refined version of the 11-step General Process for Transportation Facility Adaptation Assessments which was developed for the US DOT Gulf Coast Phase 2 project.	
Adaptive capacity	The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.	IPCC Working Group II
Adaptive management	Incremental approach to adaptation where practitioners implement one measure, monitor the conditions to see the effect, and then move to another measure as needed.	
ADvanced CIRCulation (ADCIRC) modeling	A hydrodynamic model often used for computer simulations of coastal circulation and storm surge at a high resolution.	
Aggregate interlock	The projection of aggregate particles or portions thereof from one side of a joint or crack in concrete into recesses in the other side so as to effect load transfer in compression and shear, and to maintain mutual alignment.	
Air-convecting embankment (ACE)	A specialized type of embankment consisting of large loose rocks placed in a manner to foster air movements within the embankment, helping to extract heat from the ground and keep it colder (ideally frozen).	
Annualized cost	The average cost per year of owning and operating an asset over its entire lifespan.	

Area under the curve (AUC) approach	An analytical technique used to link the probability of each weather event with the costs shown in the climate stressor-damage relationship curves to estimate a design option's lifecycle weather-related costs.	
Armoring	Hardening of infrastructure using a stronger construction material. This is commonly refers to road embankments where exposed side slopes are hardened through the placement of riprap or another damage resistant material.	
Asphalt binder	Asphalt binder is a viscous petroleum-based product that acts as the glue that holds the aggregate together.	
Asphalt concrete	Asphalt concrete (commonly referred to simply as bituminous or AC), a key component of flexible pavement design, is the term given pavement comprised of a mixture of asphalt, aggregate, and other admixtures.	
Asset management	A body of management practices applied (in this context) to infrastructure that seeks to achieve and sustain a desired state of good repair over the lifecycle of the assets at minimum practicable cost.	
Backwater	The increase in water surface elevation relative to the elevation occurring under natural channel and floodplain conditions. It is induced by a bridge or other structure that obstructs or constricts the free flow of water in a channel.	
Bascule bridge	A moveable bridge, sometimes referred to as a drawbridge, with a counterweight that continuously balances a span, or "leaf", throughout its swing to provide clearance for boat traffic.	
Beach nourishment	The direct placement of large amounts of good quality sand on the beach to widen the beach.	
Bed load	The portion of actively moving sediments within a stream / river that is not fully suspended with the water. The bed load sediments move by rolling, bouncing, or skipping along the channel bed.	
Benefit-cost analysis (BCA)	Comparison of the benefits to be generated by the project (e.g., congestion relief, safety improvements) relative to its capital costs.	

Benefit-cost ratio (BCR)	A numeric ratio that expresses the discounted total benefits of the adaptation option relative to its discounted total costs. Projects with a BCR over one have greater benefits than costs.	
Bridge substructure	Structural elements of a bridge, including bridge abutments, piers, and footings, that support the bridge superstructure and transfer loads to the earth.	
Bridge superstructure	Structural elements of a bridge, including decks, beams, and girders that support the loads on a bridge and transfer those loads to the substructure.	
Chronic climate stressors	Slow changes to climate variables over time such as gradual increases in temperature.	
Climate change	Climate change refers to any significant change in the measures of climate lasting for an extended period of time. Climate change includes major variations in temperature, precipitation, or wind patterns, among other environmental conditions, that occur over several decades or longer. Changes in climate may manifest as a rise in sea level, as well as increase the frequency and magnitude of extreme weather events now and in the future.	EO 5520
Climate impact	The impact that a climate effect has on a (transportation) asset.	
Climate models	Complex numerical models used to examine the interactions between the atmosphere, land surface, oceans, and sea ice—and estimate future climate conditions based on these analyses.	
Climate scenarios	Plausible futures that are built on different trajectories of future greenhouse gas concentrations, land use, and other factors, that are then run through climate models to project future values of temperature and precipitation.	
Climate stressor	Variation in a climate variable that may lead to a climate impact (e.g., high temperatures, heavy rainfall, cyclical variations in temperature over a period of time).	
Climate stressor-damage relationship curve	A line graph that captures the relationship between the intensity of a climate stressor and the associated damage costs.	

Climate variable	Parameters used to measure and describe climate. For example, temperature, precipitation, wind, storm surge, waves, and relative sea level change.	
CMIP3 and CMIP5	References the 3rd and 5th phase of the Coupled Model Intercomparison Project.	
COAST	Software tool for the calculations required for AUC analysis.	
Constructed soils	Embankments or soil foundations constructed to specific specifications describing the desired soils characteristics and performance.	
Construction joints	Connections between construction materials to account for the materials' movement. Movement is commonly caused by expansion or contraction of the adjacent materials from changes in temperature.	
Context-sensitive design	An engineering design model that considers the effects of aesthetic, social, economic and environmental conditions in addition to the physical design aspects of a project.	
Continuously reinforced concrete pavement (CRCP)	A type of rigid or Portland cement concrete (PCC) pavement constructed with steel reinforcing bars placed within the concrete along the entire length of the pavement. CRCP is characterized by the absence of constructed transverse joints. CRCP naturally forms tight transverse cracks to evenly transfer loads.	
Countermeasure	A measure intended to prevent, delay, or reduce the severity of hydraulic problems.	
Crushed aggregates	Good quality rock processed through a crusher.	
CUENCAS hydrological model	A two-dimensional distributed rainfall/runoff hillslope coupled hydrologic and hydraulic model developed at the University of Iowa.	
DCHP Database	Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections (DCHP) website. This is FHWA's preferred source of climate projection information.	
Debris basins	A constructed pond or basin designed for the targeted collection of debris (e.g., trash, wood, sediment, boulders) from stream flows.	
Debris flow	A slurry mixture of sediment and woody materials in stream flood flows, commonly seen in post-wildfire streams during storm events.	

Deformation	Materials damage resulting from an applied force that remains after the force is removed.	
Design life	Estimated period of time that an asset or facility is expected to last at desired performance levels given design parameters.	
Design standards	A standardized level of engineering design adopted by an agency or owner that is based upon an acceptable level of risk for the subject type of infrastructure.	
Design threshold	The temperature and moisture parameters for which a facility is designed to perform over its design life.	
Direct benefits (of an adaptation measure)	Avoided costs incurred by the agency and an asset's primary users.	
Discount rate	A key input into economic analysis that accounts for the time-value of money.	
Downscaling	Adjusting climate model outputs to the local scale.	
Dry floodproof	Designing or modifying a building, enclosure, or area to render it substantially impermeable to the entrance of floodwaters, thereby lowering the potential for flood damage. "Substantially impermeable" is usually defined as resulting in a maximum accumulation of 4 inches of water depth in a dry flood-proofed space during a 24-hour period.	
Duct banks	Typically a collection of electrical or communication cables enclosed in PVC or concrete. The term "duct bank" is typically applied to outside facilities not attached to structures.	
Dynamical downscaling	Adjusting climate model outputs to the local scale by feeding global model outputs into a higher resolution local climate model.	
Economic impact analysis (EIA)	Quantification of the economic development benefits of a project (e.g., number of jobs the project will create, urban development the project will stimulate).	
Effective stress	The forces acting on a soil mass. A relative higher effective shear stress indicates a higher resistance to shear stress.	
Emergency funding	Funding typically provided by a government agency to address specific disasters. Emergency funding is	

	usually distributed after a declaration of a "state of emergency".	
Emission scenarios	Future greenhouse gas emissions scenarios are based on a range of potential future factors such as economic growth, population, and energy consumption. These factors are translated into emissions and concentrations of greenhouse gases over time.	
Encroachment	Development or construction within FEMA designated floodplains.	
Engineering-informed adaptation studies	Site-level assessments of climate change impacts and adaptation options used to inform the project development process.	
Environmental analysis	A required study to consider the potential environmental consequences of a project, document the analysis, and make this information available to the public for comment prior to implementation.	
Eustatic sea level rise	Global sea level rise, due to change in the volume of the world's ocean basins and the total amount of ocean water. Vertical land movement is not included.	
Exceedance probability	The percent chance of the magnitude of an event being equaled or exceeded during a single year. For example, a storm with a 0.01 exceedance probability has a 1% chance of occurring in a given year.	
Exposure	The nature and degree to which a system or asset is exposed to significant climate variations.	
Extreme water levels	Water elevations associated with significant, longer return period storm events.	
Extreme weather	Extreme weather events can include 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. Climate change can also cause or influence extreme weather events.	EO 5520

Facility management plan	Typically, an element of asset management that identifies a structured, scheduled, and budgeted sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the lifecycle of the infrastructure.	
Failure plane	The geometric boundary that differentiates a sliding soil mass from the adjacent stable soil mass.	
Fatigue cracking	Cracking that occurs from repetitive stress on a material.	
Fetch	The distance or area in which wind blows across the water forming waves.	
Final design/engineering	Final design and engineering means any design activities following preliminary design and expressly includes the preparation of final construction plans and detailed specifications for the performance of construction work.	
Flexible pavement	Pavement that is elastic under traffic loading. Typically asphalt concrete or bituminous treated aggregate ("prime and seal surface treatment").	
Flood gate	A movable gate used to control or block the flow of water.	
Freeboard	Clearance above the peak water surface for a particular storm event. Measurement can be defined differently for different types of infrastructure, i.e. bridges may define freeboard relative to the bottom of the bridge deck, roadways may define it relative to the lowest point of the roadway shoulder, while levees will define it relative to the top elevation along the levee.	
Freeze-thaw event	A temperature fluctuation where temperatures first drop below freezing, and then rise above freezing. There can be multiple freeze-thaw events in a day.	
Frost heave	An upward swelling of a portion of the pavement caused by the formation of ice crystals in a frost-susceptible subgrade or base course. In pavements, differential frost heave may create bumps along the roadway resulting in hazardous driving conditions.	
Geosynthetic reinforcement	A geotextile or other geosynthetic material used to strengthen a roadway pavement system.	

Geosynthetics	A planar product manufactured from polymeric material used with soil, rock, earth, or other geotechnical engineering related material as an integral part of a man-made project.	
Geotextiles	A strong synthetic fabric usually used to stabilize loose soil, separate pavement system layers, or prevent erosion.	
Green infrastructure	Natural and nature-based solutions to increase resilience and provide habitat.	
Headwater to diameter ratio (HW/D)	A culvert design criterion that compares the headwater depth (HW), measured from the water surface to the culvert inlet invert, to the culvert diameter (D) or rise.	
Historic landmarks	Features (bridges, roadways, homes, etc.) included or eligible for inclusion on the National Register of Historic Places. Properties listed on the Register have been deemed worthy of preservation.	
Hydraulic models	Theoretical/computational models of river flow dynamics, producing water surfaces, depths, and velocity results at defined river flow rates.	
Hydrodynamic model	A computer program that simulates the movement of water based on the fundamental equations of motion.	
Hydrologic models	Theoretical/computational models of watershed rainfall and runoff dynamics, producing estimated river flow rates for input precipitation amounts.	
Hydrologic probability	The probability of storm occurrence over a defined period of time, usually the remaining service life of the asset being analyzed (greater than 1-year).	
Hydromulching	Spraying of a mixture or tackifiers, water, mulch, and seed over exposed soils to promote the establishment of grasses and other plants.	
Hydrophobicity	The resistance of burned soils from infiltrating water.	
Hydrostatic pressure	The pressure exerted by a fluid at equilibrium at a given point within the fluid, due to the force of gravity.	
Ice richness	Describes the amount of ice contained in frozen or partially frozen soil or rock -- on either a dry-weight basis (gravimetric) or on a volume basis (volumetric). The higher the value, the higher the ice content.	

Impervious surface	Developed areas of land where infiltration of precipitation into the ground is not possible due to overlaying pavement, buildings, etc.	
Impact Analysis for Planning (IMPLAN)	Economic impact modeling software.	
In situ soils	Soil in its un-disturbed state.	
Indirect benefits	Avoided costs incurred by entities that are not direct users of the asset, but would be affected by climate impacts to the asset.	
Intelligent Transportation Systems (ITS)	E.g. ramp meters, roadway sensors, variable message signs.	
Intensity-Duration-Frequency (IDF) curves	A graph or mathematical equation that relates the rainfall intensity (I), storm duration (D), and exceedance frequency (F). Durations generally range from 5 minutes to 24-hours and longer.	Adapted from HDS-2
Junction boxes	An enclosure (box) that can provide access to the connections of electrical or communication cables.	
King tides	Non-technical term for extremely high tide levels due to regular astronomical (interactions of the sun/moon/earth system) fluctuations.	
Lifecycle cost analysis (LCCA)	Comparison of the lifecycle costs of different design alternatives.	
Lifecycle costs	Initial capital outlays plus long-term management costs, including material and labor costs as well as traffic disruption costs.	
Living shoreline	An alternative for shoreline stabilization that uses natural and organic materials that complement the natural shoreline while providing suitable habitat for local species.	
Long Term Pavement Performance Bind (LTPPBind)	FHWA online software tool for selecting Superpave® asphalt binder grades using nationwide mapping of design temperatures based on historical weather data.	
Manufactured fines	Rock (aggregate) processed through a crusher to small particle sizes which are defined by engineering specification.	
Mechanical deformation	Deformation caused by the added contribution to settlement of the weight of vehicles on the road and the weight of the embankment.	

Micropiles	A small diameter, bored, cast-in-place pile, in which most of the applied load is resisted by the steel reinforcement.	
Monte Carlo analysis	An analytical technique used to link the probability of a weather event with the costs shown in the climate stressor-damage relationship curves. This analysis estimates a design option's lifecycle weather-related costs by creating a multitude of storylines of possible weather events over an asset’s lifespan.	
Nautical miles	A unit often used to measure distance at sea, approximately equal to the length of a minute of arc. Approximately 6,076 feet, 2,025 yards (1,852 meters) or 1.15 times as long as the U.S. statute mile of 5,280 feet.	
Negative-bending	The bending of a structural member fixed at the ends and loaded in the upward vertical direction, characterized by tension stresses in the top portions of the member.	
Net present value (NPV)	The difference between the discounted total benefits of the adaptation option and the discounted total costs.	
Non-stationarity	A characteristic of time series data such that the data are heterogeneous. Trends over time prevent historical data from being used to estimate future conditions. That is, a situation where historic conditions or patterns may not be valid in the future.	Adapted from HEC-17
Ongoing costs	Recurring costs over an assets lifetime, such as maintenance.	
Operator houses	Rooms typically connected to facilities such as tunnels or movable bridges that house the persons operating the facility.	
Overtopping	Passing of water over the top of a structure (e.g., seawall, roadway) usually as a result of wave runup or coastal storm surge action. Riverine flow can contribute to overtopping.	
Overwashing flow	Sustained movement of water over the top of a barrier island or roadway as a result of coastal storm surge.	

Parametric analysis	An analysis that, in general, varies a constant or variable term in a function that determines the specific form of the function but not its general nature. For example, altering a in f (x) = ax to see the effect on f (x) where a determines the slope of the line described by f (x).	
Pavement base course	The layer or layers of aggregate, asphalt concrete or concrete below the surface pavement course.	
Pavement distress	Pavement deformation or other failure.	
Pavement subgrade	The soils beneath the pavement base course.	
Pavement surface	The top layer of paving material.	
Peak storm flow	The maximum amount of instream flow (measured as volume per unit time - e.g. cubic feet per second) during a specific storm event.	
Performance threshold	The temperature and moisture conditions for which a facility must maintain its serviceability over its service life.	
Pile plate	A plate fastened to a pile to increase its load-carrying capacity.	
Planning	A process to articulate the transportation system need that a project will address.	
Practical design process	The practice of scoping projects to stay within the core purpose and need, expected to result in lower cost and improved value.	
Preliminary design/engineering	The process of collecting more detailed information to inform the development of a project by conducting field investigations, other technical studies (e.g., environmental studies, climate change studies), and preliminary engineering studies.	
Projections	A modeled forecast of future climate conditions.	
Punchouts	Localized slab failures characterized by closely spaced transverse cracks often connected by short longitudinal cracks and joints.	
Regional Economic Models Inc. (REMI)	An input-output regional economic model that represents inter-industry relationships.	
Relative humidity	The amount of water vapor present in air expressed as a percentage of the amount needed for saturation at the same temperature.	
Relative sea level rise	Sometimes referred to as local sea level rise, measured at a coastal location relative to the land. This includes both the eustatic sea level rise	

	component and the vertical land movement (local subsidence, uplift, etc.) component. This is the sea level change measured by long-term tide gages.	
Representative concentration pathway (RCP)	Four greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014.	IPCC AR5
Resilience	Resilience or resiliency is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.	EO 5520 definition
Return period	A concept used to define the average length of time between occurrences in which the value of the random variable, typically flood level, is equaled or exceeded. Also known as the recurrence interval.	
Rigid pavement	Pavement with high flexural strength, typically concrete pavement.	
Riparian	Related to or located on the banks of a stream or river.	
Risk	The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability or likelihood of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. The concept of flood risk typically captures both the probability of the flood event and the consequences of the flood event.	IPCC Working Group II
River geomorphology	The study of the shape and condition of river channels and how they change over time.	
ROADAPT	A climate change adaptation framework and accompanying tools developed in Europe.	
Rock revetment	A layer or layers of stone used to protect an embankment or shore structure against erosion by wave action or currents.	
Rutting	A surface depression in the wheel paths caused by permanent deformation in any of the pavement layers or soil subgrade due to repeated traffic loading.	
Saffir-Simpson hurricane category scale	A 1 to 5 rating of a hurricane’s sustained wind speed.	

Scenario uncertainty	Uncertainty introduced into climate projections due to limitation in accurately predicting human behavior. Sometimes referred to as human uncertainty.	
Scenarios approach	A technique used to estimate a design option's lifecycle weather-related costs by evaluating the asset's performance under a series of plausible scenarios of weather-related event occurrences.	
Scientific uncertainty	Uncertainty introduced into climate projections due to limitations in scientific knowledge or model capabilities. Sometimes referred to as model uncertainty.	
Scoping	Scoping in this context refers to general scoping activities that take place pursuant to project development, including activities prior to NEPA initiation, rather than scoping as formally defined in NEPA regulations at 40 CFR 1501.7.	
Sea level rise	A rising long-term trend in mean sea level.	
Sensitivity test	Testing the robustness of analysis outcomes to individual inputs by varying them one at a time. This test provides insight on which inputs more significantly drive the analysis outcomes.	
Shear strength	The peak shear stress a material can sustain before failure.	
Shear stress	A force that causes layers or parts to slide upon each other in opposite directions.	
Shoreline recession	Landward movement of the shoreline. A net landward movement of the shoreline over a specified time.	
Shrinkage cracking	Hairline cracks formed during concrete setting and curing.	
Shrink-swell effects	Damages caused to pavements constructed on soils that are highly sensitive to moisture that swell when wet and shrink when dry. This damage typically results in a loss of pavement smoothness.	
Simulating WAves Nearshore (SWAN) model	A computer model that simulates wave generation, propagation and transformation in coastal regions and inland waters at a high resolution.	

Slope factor of safety	The ratio of shear stress to available shear strength along a failure plane. Values less than one indicate an unstable slope at high risk of failure. Permanent slopes are typically designed to a factor of safety of 1.5.	
Smoothness deterioration	Degradation of the pavement surface evenness.	
Soil nails	Reinforcement drilled into soil slopes and grouted to support excavations in soil rock. Soil nails are considered reinforcing elements that: (a) contribute to the stability of earth-resisting systems mainly through tension resulting from deformation of the retained soil or weathered rock mass; (b) transfer tensile loads to the surrounding ground through shear stresses (i.e., bond stresses) along the grout-ground interface.	
Special Flood Hazard Areas (SFHAs)	The SFHA is the land area covered by the floodwaters of the base flood on NFIP maps. The base flood has a 1 percent chance of being exceeded in any given year. In the SFHA the National Flood Insurance Program's (NFIP's) floodplain management regulations must be enforced and purchase of flood insurance is mandatory. FHWA policy is to be consistent with the intent of the Standards and Criteria of the NFIP where appropriate.	
Spring load restrictions	Policies to regulate the axle load of trucks during the spring thaw period. Under Spring Load Restriction policies, a highway agency will typically reduce the maximum allowable weight by as much as 90 percent from their normal legal limits.	
Stationarity	The characteristic of time series data such that the data are homogeneous. There are no trends that would prevent historical data from being used to estimate future conditions. That is, indicates historic conditions are expected to be valid in the future.	Adapted from HEC-17.
Statistical downscaling	Adjusting climate model outputs to the local scale based on the statistical relationship between local weather variables (e.g., surface rainfall) and larger-scale climate variables (e.g., atmospheric pressure).	

Storm surge	The rise of the mean water level above the astronomical tides due to all meteorological forcing (e.g. winds, pressure, precipitation).	
STWAVE model	A computer model that simulates nearshore wave generation, propagation and transformation in coastal regions and inland at a high-resolution.	
Subsidence	Land subsidence is a gradual settling or sudden sinking of the Earth's surface due to the removal or movement of subsurface earth material.	NOAA
Tailwater conditions	Stream/river flow depths at the downstream end of a culvert or bridge.	
Thermal deformation	Deformation caused by temperature's effect on permafrost thaw and roadway settlement.	
Toe wall	A wall placed at the bottom (toe) of an earthen slope intended to prevent earth sliding.	
Total costs	The costs to build and maintain the design option plus the expected damage and socioeconomic costs over the asset’s lifespan.	
Underdrains	A perforated pipe installed beneath the ground surface to drain ground water (deep) or intercept and drain surface water seepage (shallow).	
Upfront costs	The initial costs of project development and construction including all associated costs (e.g., design, permitting, traffic control).	
Upland erosion controls	Small scale features constructed along hillslopes to prevent generation of eroded soils in the upper portions of the watershed, near the erosion source.	
Uplift	Upward movement of the Earth's surface relative to a geodetic datum. Results in increased elevation.	
US DOT CMIP Climate Data Processing Tool	An Excel based tool that processes readily available downscaled climate data at the local level into relevant statistics.	
Useful life	Estimated period of time that an asset or facility is expected to provide desired levels of service given demand and environmental stresses.	
Utility conduits	Typically a collection of electrical or communication cables enclosed in a protective cover such as PVC or concrete.	

Value engineering process	A systematic process of review and analysis of a project, during the concept and design phases, that is conducted to provide recommendations for: providing the needed functions safely, reliably, efficiently, and at the lowest overall cost; improving the value and quality of the project; and reducing the time to complete the project.	
Variances	Exceptions to zoning laws or other regulations that address specific concerns.	
Volatiles	Petroleum compounds that are used in some asphalt mixes to make them more pliable.	
Vulnerability	The extent to which a transportation asset is susceptible to sustaining damage from hazards (including climatic). Vulnerability is a function of exposure, sensitivity, and adaptive capacity.	
Wave attack	The action of waves impacting or acting on a structure, embankment or shoreline.	
Wave runup	The uprush of a wave's water up a slope or structure.	
Waves on surge	The combination of waves on increased water levels due to storm surge.	
Weather	The meteorological and atmospheric conditions at a particular place and time, including temperature, precipitation, wind, etc. Weather represents conditions over a short period of time; climate, meanwhile, represents conditions over longer periods.	
Wet floodproof	Allows water to enter the structure/asset but limits or prevents damage to critical components.	
Wildfire impairment	Refers to conditions where a wildfire has negatively impacted the hydrologic process of a watershed.	
Wildfire models	The numerical simulation of wildland fires to understand and predict fire locations and behavior.	
Winter weight premiums	Policies that allow heavier truck loads during times when the ground is frozen, since frozen ground provides more support to the pavement system.	

Appendix E: Incorporating Climate Change into Transportation Decision Making Meeting Attendees

On June 28, 2016, the following individuals participated in a stakeholder meeting to discuss the lessons and topics covered in this report.

Name	Affiliation
State Departments of Transportation	
Charlie Hebson	Maine Department of Transportation
Julie Heilman	Washington Department of Transportation
Wade McClay	Maine Department of Transportation
Steven Miller	Massachusetts Department of Transportation
Curran Mohney	Oregon Department of Transportation
Dana Morse	Maryland State Highway Administration
Karuna Pujara	Maryland State Highway Administration
Brian White	Washington Department of Transportation
AASHTO	
Shannon Eggleston	AASHTO
Keith Platte	AASHTO
Federal Affiliations	
Federal Highway Administration	
Scott Anderson	FHWA Resource Center
Brian Beucler	FHWA
Eric Brown	FHWA Resource Center
Mike Culp	FHWA
Heather Holsinger	FHWA
Rob Hyman	FHWA
Rob Kafalenos	FHWA

Joe Krolak	FHWA
Becky Lupes	FHWA
Khlaid Mohamed	FHWA
Anthony Serna	FHWA
Tom Yu	FHWA
US Army Corps of Engineers	
Roselle Henn	USACE
Kate White	USACE
US Geological Survey	
Stacy Archfield	USGS
Other Affiliations	
Josh DeFlorio	Port Authority of New York and New Jersey
Hani Farghaly	Ontario Ministry of Transportation
Rawlings Miller	Volpe
Anne Choate	ICF
Brenda Dix	ICF
Angela Wong	ICF
Scott Douglass	SCE
Chris Dorney	WSP
Justin Lennon	WSP
Jag Mallela	WSP
Claire Bonham-Carter	AECOM