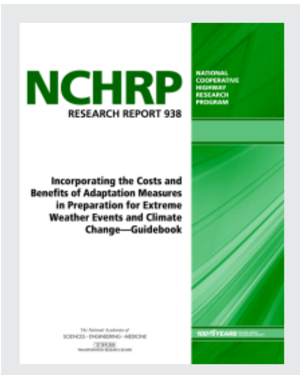

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 938

Incorporating the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change—Guidebook

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2020

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration (FHWA), United States Department of Transportation, under Agreement No. 693JJ31950003.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the National Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments, by committees of AASHTO, and by the FHWA. Topics of the highest merit are selected by the AASHTO Special Committee on Research and Innovation (R&I), and each year R&I's recommendations are proposed to the AASHTO Board of Directors and the National Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

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FOREWORD

By Stephan A. Parker
Staff Officer
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This report provides an overview of the current state of the practice on the use of cost-benefit analysis (CBA) in the decision-making process within transportation agencies, identifies how CBA can be incorporated into transportation-planning processes along with climate adaptation, and develops two frameworks for evaluating the potential cost-effectiveness of incorporating climate adaptation measures into projects. This report has the potential to serve as

- A single resource that summarizes the current state of the practice for incorporating CBA into adaptation planning and analysis;
- A source for identifying existing, relevant data and tools to support CBA for adaptation planning; and
- An intuitive guide for incorporating CBA into state and local transportation asset management and planning policies and procedures that incorporate climate change and extreme weather adaptation planning.

Extreme weather events and a changing climate can result in significant costs to transportation agencies, to the traveling public, and to communities. State departments of transportation (DOTs) as well as other public infrastructure agencies are increasingly challenged with difficult decisions about whether, when, and to what extent to incorporate adaptation measures into their existing and future facilities to provide more resilience in the event of extreme weather or in response to the evolving effects of climate change. Given the potential costs and benefits involved in enhancing the resilience of transportation systems, the decision to implement adaptation measures is dependent on a variety of factors. Improved guidance will assist transportation decision makers in making informed and supportable decisions regarding implementation of adaptation measures for extreme weather events and climate change. The return on investment will be realized from making better long-term decisions based on a more holistic analysis of the costs and benefits of implementing adaptation measures.

Under NCHRP Project 20-101, "Guidelines to Incorporate the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change," a research team led by Dewberry Engineers developed a methodology and handbook for practitioners to use in conducting a simple CBA by hand or with a spreadsheet to evaluate the most cost-effective climate and extreme weather adaptation and response. The team began with a literature review, conducted a survey of current practices at state DOTs around the country, and followed up with in-depth telephone interviews of practitioners. The team's aim was to gain a broad understanding of the tools, methods, data, and models used by practitioners; their decision-making processes; and perceived needs. A gap analysis informed a recommended framework and architecture to organize existing tools, methods, and data for practitioner use and built on existing resources based on the needs identified in the gap analysis. The framework and architecture considered both capital cost components and non-capital cost components such as environmental impacts.

This research produced additional resources (available on the TRB website at http://www.trb.org/Main/Blurbs/180405.aspx), including a PowerPoint presentation that describes the research and the results; a spreadsheet tool that provides an approximate test to see if it would be cost-effective to upgrade assets to the future conditions posed by climate change; a second spreadsheet tool that (1) uses existing conditions without climate change only to calculate the new return period for future conditions with climate change and (2) also calculates a benefit-cost ratio that can be used by decision makers to evaluate whether an adaptation project would be a worthwhile investment. The contractor's final report that describes the methodologies used is provided on the TRB website as *NCHRP Web-Only Document 271* at http://www.trb.org/main/blurbs/180536.aspx.

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Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

SUMMARY

Incorporating the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change—Guidebook

State departments of transportation (DOTs) are facing a daunting challenge in the coming years: they need to find ways to repair and replace aging infrastructure that the ASCE scored between a D and a C+, they need to do it in a way that allows the assets to adapt to and recover quickly from extreme weather events and climate change, and they need to accomplish these tasks with budgets that are static or dwindling. In short, state DOTs need to find ways to optimize scarce resources.

In the face of changing climate and an increase in extreme weather, tools that address cost-effectiveness can help DOTs make informed decisions about how to invest their limited funds. Cost-benefit analysis (CBA) is one tool available to DOTs to help them evaluate if and how to incorporate adaptation for climate variability and extreme weather by quantifying the benefits and costs of a project or policy using an equivalent monetary value for each alternative. Research for Project 20-101 revealed that while DOTs are taking into account changing climate and extreme weather when making infrastructure decisions, they typically are not using a formal set of tools or CBA to address climate resilience.

When transportation practitioners are questioned about why they do not typically conduct a CBA as part of their investment decision-making processes, many reveal their perception that CBA is too time-consuming and expensive to conduct routinely; CBA is done only for projects above a certain cost threshold or for grant applications that require it. For CBA and other decision-making tools to be routinely useful, DOTs indicated these tools need to

- Leverage existing data and processes to the greatest extent possible,
- Complement existing methods and policies,
- Yield results in net present value, and, most importantly,
- Be simple to use.

While many frameworks and tools offer elements needed to perform a climate-informed project-level CBA, no single framework or tool meets the criteria desired by transportation practitioners.

This guidebook was developed to fill the gaps identified by DOTs. It is intended to provide a consolidated resource for transportation practitioners to more readily consider CBA as a tool in investment decision making when considering different climate and extreme weather adaptation alternatives. Chapters 1 through 6 provide information about CBAs, using CBA as part of the investment decision-making process, and climate change:

- Chapter 1 summarizes why and how this guidebook was developed, and introduces a fictitious scenario used throughout the guidebook to illustrate concepts discussed in each subsequent chapter.
- Chapter 2 provides an overview of CBA—different types such as project-level and triple bottom-line CBAs; metrics such as net present value and benefit-cost ratio; and impacts of funding sources, such as grants and loans, on CBAs.
- Chapter 3 provides an overview of climate change considerations. Selection of climate scenarios and time frames will influence which adaptation alternatives will be cost-effective. The chapter discusses accounting for non-stationarity and provides guidance on how to evaluate whether climate adaptation will be considered.
- Chapters 4 and 5 discuss common costs and benefits used to conduct CBAs, and also include information about environmental, social, and safety considerations incorporated in a triple bottom-line CBA.
- Chapter 6 provides practitioners with information about selecting alternatives and analysis time frames for completing a CBA, to allow appropriate time frames and alternatives to be incorporated into the transportation-planning process.

The culmination of the research conducted for this project is the development of an approach that allows practitioners to conduct short, simple CBAs to evaluate if climate and extreme weather adaptation strategies might be cost-effective. The approach, which includes two levels of analysis, was developed to be consistent with methods described in FHWA's Hydraulic Engineering Circular 17, "Highways in the River Environment: Extreme Events, Risk and Resilience." A Study Level 1 analysis as described in Chapter 7 provides an approximate test to evaluate if incorporating adaptation measures would be cost-effective. A Study Level 2 analysis as described in Chapter 8 builds on a Study Level 1 analysis to return a benefit-cost ratio and net present value of costs and benefits under future climate conditions. The analysis levels are applied to case studies that have already completed CBAs; a comparison shows results between the case study CBAs and the results from the simplified approaches are consistent, suggesting that the simplified approach could be a useful screening tool for transportation practitioners deciding whether to consider incorporating climate and extreme weather adaptation into capital-improvement projects. Spreadsheet tools were created in Excel for Study Level 1 and 2 analyses. These tools are available for users of this guidebook to download; to access them, search the TRB website for "NCHRP Research Report 938". Each workbook includes an example from the guidebook calculated at two different discount rates and also a blank tab for users to input their own project data. Also available on the TRB website is the contractor's final report on NCHRP Project 20-101, which is published as *NCHRP Web-Only Document 271* (available at http://www.trb.org/main/blurbs/180536.aspx).

Increasingly frequent weather events present potentially serious and costly impacts on an aged, already-taxed transportation infrastructure. In the face of these extreme events, transportation practitioners need tools and policies that help them make informed decisions about how to invest limited financial resources. CBA is one tool that can help strengthen the case for making climate-resilience investments, particularly because the peak benefits could be realized later in the infrastructure life cycle. CBA does have some limitations, such as the inability to monetize all of the benefits associated with a project or policy. Yet it is a useful tool in the transportation-planning toolbox to help practitioners screen projects and adaptation approaches, then identify those for further consideration of incorporation into a project.

CHAPTER 1

Introduction

Synopsis of Issue

Extreme weather events and a changing climate increasingly boost costs to transportation agencies and to the traveling public. The World Meteorological Association reports that the world is nearly five times as prone to weather-related disasters now as it was in the 1970s. This change in the frequency and severity of extreme weather events in the United States has already increased travel delays (10 to 24 percent) and crash risks (by 24 percent on slick pavement or in adverse weather). Extreme weather events also reduce traffic speed and roadway capacity, disrupting access. Fifteen percent of all road congestion is due to bad weather and 25 percent is due to incidents, costing the United States over $9.45 billion per year just in major urban areas. Weather-related delays add $3.4 billion to freight costs annually. Altogether, the societal cost of adverse weather in terms of crashes, fatalities, injuries, and property damage through 2055 is estimated to be $23.074 trillion (Guevara, 2013).

In recent years, state DOTs have begun to understand that the organization and availability of their personnel and equipment are as critical to their agencies as the performance of the physical infrastructure system and the short-term budget and system restoration priorities. For example, the 2010 Tennessee floods, a 1,000-year event, required 83,000 state DOT maintenance hours to deal with damage in 41 counties. Damage included sinkholes up to 25 feet wide and deep that developed 2 weeks after the initial floods, closing Interstate 40 (*Transportation Research Circular E-C152*, 2011). Increasing storm damage and flooding have a significant adverse impact on DOT operating budgets, which are absorbing costs for more risk communication to the public, road repairs related to heat buckling, or more extensive problems caused by extreme storms and floodwaters to roads, road bases, bridges, and culverts.

As states have begun to experience the impacts of the increasing frequency of extreme weather events on their systems, many state DOTs have started to evaluate factors such as criticality, traveler delays, economic impacts on freight, emergency management needs, and safety, and to include these factors when evaluating the implications of climate change on their systems and the cost-effectiveness of possible improvements. For example, the Washington State DOT studied one 4-day closure and estimated $18 million in damages to state highways, as well as freight-related economic impacts of $47 million in lost economic output, $2 million in lost state tax revenues, and $14 million in lost personal income (Ivanov et al., 2008).

To make the best use of limited resources and achieve the best results possible in the face of extreme weather, state DOTs need to understand what data and tools are available to help them make informed, timely decisions by weighing the benefits and costs of different feasible courses of action given the situational constraints. Cost-benefit analysis (CBA), also referred to as benefit-cost analysis (BCA), is one tool decision makers can use to evaluate if and how to incorporate climate change adaptation or extreme weather into the design of a transportation asset or system.

Target Audience

This guidebook is intended to assist an audience with varying levels of knowledge and experience with CBA and climate adaptation related to transportation assets. For those with little knowledge or experience working with CBA, the guidebook provides background information about what these analyses are and why they are conducted, different types of CBAs, factors that contribute to the development of a CBA, and how results might be interpreted using different metrics. For those with little knowledge of climate change, the guidebook provides some background information about the most commonly used climate models and how they can be applied in the context of a CBA. For those with more experience, the guidebook provides information about how a climate-informed CBA could be conducted and provides examples of how to incorporate climate predictions into CBAs.

Why Was the Guidebook Developed?

State DOTs and other public infrastructure agencies are increasingly challenged with difficult decisions about whether, when, and to what extent to incorporate adaptation measures into existing and future facilities to provide more resilience in the event of extreme weather or in response to the evolving effects of climate change. NCHRP has developed guidance that enables transportation decision makers to integrate analysis of the costs and benefits of adaptation measures in preparation for extreme weather events and climate change. Such rigorous analysis will benefit practitioners making planning and funding decisions in a fiscally constrained environment.

How Was the Guidebook Prepared?

The authors of this guidebook conducted an extensive literature review that considered existing research; tools, methods, and data for traditional cost-benefit analysis frameworks; hazard mitigation frameworks; transportation capital planning and investment frameworks; operations, emergency response, and recovery-planning frameworks; and climate-resilience frameworks. The authors also considered recent federal-level transportation policy and funding drivers and their potential impacts on policies and goals at the state and local agency levels. In addition to conducting desktop reviews, the research team disseminated a survey to DOTs regarding their current use of CBA and their experience with resilience planning for climate adaptation and extreme weather events. The team supplemented the information received from the survey by conducting interviews with DOT personnel to further understand their experiences, challenges, and successes with resilience planning and use of CBA as a decision support tool. The guidebook summarizes these findings and uses them as a practical basis to provide a clear picture of the issues and to facilitate development of frameworks to address these challenges.

The frameworks the research team developed maintain consistency with existing guidance from federal agencies such as the FHWA and the Federal Emergency Management Agency (FEMA), with the idea that these approaches may be most familiar to users. The frameworks were also developed so that CBAs could be completed by hand if necessary, provided the needed data inputs are available. Required data inputs can be obtained or calculated from existing, often readily available, data sets and tools.

What Specifically Does the Guidebook Provide?

This guidebook provides a summary and an explanation of the information needed to complete CBAs at varying levels of analysis. It explains the key parameters included in any CBA, as well as different types of CBAs, the data required for each type of analysis, and potential data sources.

It allows users to evaluate whether climate or extreme weather adaptation measures are viable at the asset or corridor levels from a financial or triple bottom-line perspective and, if so, the allowable value of the measures that could be implemented to maintain a positive net present value for the project.

Chapters 2 through 5 of this guidebook provide educational background information about the components of CBA, climate considerations, and common costs and benefits and how they are quantitatively and qualitatively evaluated. This guidebook uses a fictitious scenario to illustrate the various principles involved with completing a CBA. The scenario was developed based on the assumption that a DOT has already completed a risk analysis of assets and corridors as part of its transportation asset management process.

People experienced with CBA or interested in getting straight into conducting a climate-informed CBA might elect to skip Chapters 2 through 5 and go straight to Chapter 6.

The Scenario

A road in Chesterfield County, Virginia, has been identified during the asset management risk analysis as being a critical facility to the local transportation network. Hydraulic structures that support the road are scheduled for replacement, and the Virginia DOT is trying to determine if certain adaptation measures should be incorporated into the designs for the replacement structure. Are such measures needed to accommodate additional risk associated with increased flows from extreme weather or climate risks that could lead to flooding and wash out the road? The current metal culvert is designed to withstand a flood event that has a return period of 50 years, which corresponds to a flow of 9,000 cubic feet per second. A cost-benefit analysis will be conducted for the current culvert as well as for the adaptation options being considered, and will be used in the decision-making process. Data gathering for the analysis is commencing.

Data needed at this stage include

- Facility of concern,
- Geographic location of the facility or corridor under consideration,
- Hazards of concern, and
- Current design criteria:
  - Flow rate (or other parameter of interest) for the hazard of interest design event and
  - Recurrence interval for the hazard of interest design event.

CHAPTER 2

Cost-Benefit Analysis Overview

Introduction

Scientific studies widely show climate is beginning to exacerbate extreme weather. Higher temperatures mean more evaporation and moisture in the atmosphere and stronger storms, droughts, and heat waves. With this in mind and looking at the increases in heavy rainfall, rising heat, and higher storm surges in store, DOTs are preparing for

- Increased incidence and magnitude of extreme events common to the region;
- Unseasonal or unusual types of extreme weather hazards;
- Impacts to vehicles (e.g., tires of trucks, ability of planes to fly) and the transportation system (e.g., road closures and vulnerability to flooding);
- Impacts to citizens and travelers and their needs related to the transportation system (e.g., access, evacuation); and
- The gradual shifting of climate zones outside the parameters for which infrastructure may have been designed (Meyer et al., 2014), potentially reducing an asset's life span, including
  - Higher maximum temperatures (affecting pavement binders, rails, and transportation operations);
  - Wetter or drier climates, depending on geography;
  - Changes to expected types of seasonal precipitation; and
  - Rising sea level.

Effective planning for resilience acknowledges that "1-in-100-year events" have been occurring at closer to 5-, 10-, and 15-year intervals in some areas, affecting DOTs around the country. Many more catastrophic events encountered in the last decade, such as the 2013 floods in Colorado, are closer to 1-in-1,000-year events (Minchon, 2013) or 1-in-500-year events, such as the hurricanes and floods in South Carolina in 2015 (Holmes, 2015) or in Texas repeatedly.

Tools and frameworks that address cost-effectiveness can help DOTs make informed decisions about how to invest limited funds in the face of changing climate and increased incidence of extreme weather. Cost-benefit analysis (CBA) for climate adaptation helps provide a rigorous foundation for communication and decision making, improving stewardship of limited public monies and overall transportation system resilience. Theoretically, as more comprehensive ranges of impacts can be included along with discount rates that treat all groups equally, CBAs will increase in value for decision making at multiple levels of government. CBAs can help strengthen the case for resilience investments, particularly because peak benefits usually occur later in the infrastructure life cycle (Coley, 2012).

In some cases, CBA may also help illustrate both the extent of need and the limits on what is affordable through adaptation, providing feedback to legislatures, councils, and other decision makers on the cost of climate change and what is more or most affordable. Research on disasters and recovery has shown that prevention is a worthwhile investment many times over. Several years of TRB workshops on climate change adaptation and CBA concluded that discounting the future and the magnitude of likely costs is a problem, pointing to a need to extend research and work toward prevention and mitigation. Planning and resilience entail recognizing that weather extremes are not as extraordinary as they once were, and DOTs need to incorporate this "new normal" into planning and decisions about what is worthwhile. Transportation agencies need effective CBA methodologies to develop long-term plans with partners and efficiently select between project alternatives, allowing them to prepare, respond, and recover quickly.

The following sections provide information about CBA—what it is and different types of CBAs, how CBA is traditionally used, and some economic factors to consider.

Cost-Benefit Analysis Definition and Use

Cost-benefit analysis (CBA), also known as benefit-cost analysis (BCA), is a formal way of organizing evidence of the good and bad effects of projects and policies. CBA is a process that tries to quantify the benefits and costs of a project or policy using equivalent monetary value, to evaluate if the project or policy meets financial and other criteria for implementation. The objective of a CBA may be to decide whether to proceed with a project, to place value on a project, or to decide which of various possible alternatives would be the most beneficial (Figure 1).

The actions DOTs take and the policies they consider or enact in response to extreme weather events and climate change can have significant cost implications. DOTs need to ensure that any adaptation measures they consider implementing will provide long-term cost savings. They need to be able to evaluate the trade-offs between different climate responses and adaptation measures and their effectiveness in terms of cost and other values. CBA provides an overview of options for assets at a specific location, experiencing a particular hazard or set of hazards, over a certain period of time.

CBA is usually most effective when incorporated into the planning process (Figure 2). This guidebook assumes that transportation agencies have already completed at least preliminary vulnerability and criticality analyses of transportation assets and corridors to identify those that might benefit from adaptation strategies. FHWA has developed publications on how to evaluate

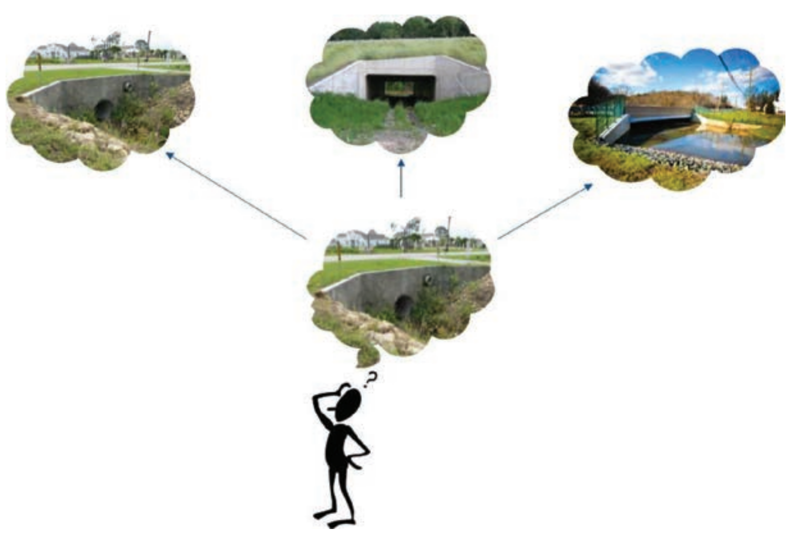

Figure 1. CBA can help transportation agencies evaluate investment alternatives.

Figure 2. The transportation sector has begun performing vulnerability assessments, but does not usually have a formal CBA framework to distinguish between adaptations addressing identified vulnerabilities. CBA is a key link between climate vulnerability assessments and adaptation implementation.

transportation assets and corridors for vulnerability and criticality, such as the *Vulnerability Assessment and Adaptation Framework,* 3rd Edition (https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/index.cfm), and *Assessing Criticality in Transportation Adaptation Planning* (https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/assessing_criticality/index.cfm). In addition, the Conference of European Directors of Roads (2016) has developed some questions to assist with incorporating climate adaptation into planning:

- What challenges do you want to address (e.g., flooding, storm surges, strong winds, increasing heat, sea level rise, rising or falling groundwater level, rockfalls, avalanches, river flooding)?
- What is the existing state of the road network? How vulnerable is it? Do you have any experience of former climate- or weather-induced incidents, and where in the organization can you find the knowledge?
- How do you want to measure (and talk) about the future? Human fatalities, number of incidents, hours of delay, miles of closed road sections?
- What kinds of incidents are covered by the strategy?
- Is the strategy for both existing and planned roads?
- What data are available (e.g., topographic maps, drainage, risk maps)?
- What instruments and tools are available (e.g., risk-identification methods, databases for incident statistics)?
- Can you do a CBA on different solutions?

Further, the European Commission and the European Environment Agency partnered to form the European Climate Adaptation Platform, also known as Climate-ADAPT. Climate-ADAPT supports adaptation by helping users access and share data and information about expected climate change in Europe, current and future vulnerabilities, strategies and action, and potential adaptation options and tools. ROADAPT is part of Climate-ADAPT and provides guidelines for adaptation of road infrastructures to climate change. While ROADAPT focuses on Europe, some of the processes and strategies are transferable or adaptable to North America (European Commission and European Environment Agency, 2015).

Once planners decide which areas, assets, or corridors to evaluate for possible inclusion of adaptation measures in future designs, they can consider performing CBAs to help them evaluate alternatives.

Steps in Conducting a Cost-Benefit Analysis

CBAs are typically conducted using a logical, structured process. In its Cost-Benefit Analysis Guide, the U.S. Army has defined an eight-step CBA process, as shown in Figure 3 and further explained as follows:

1. **Define the problem/opportunity.** Develop a problem statement that clearly states the problem to be solved or the opportunity to be addressed.
2. **Define scope; develop facts and assumptions.** The scope includes what will be covered in the project along with specific information such as duration, location, and so on. The assump-

Figure 3. Eight-step process for conducting a cost-benefit analysis (after the U.S. Army Cost Benefit Analysis Guide, 2013).

tions provide additional information about the conditions being used as the basis for the CBA. When determining assumptions, it is important to establish a baseline, that is, the status quo, against which identified alternatives will be evaluated.

3. **Define alternatives.** Alternatives are the adaptation strategies that could help address the problem or achieve the objective. One alternative always included in the analysis is the base case, also known as the status quo, in which the existing solution continues to be used. The alternatives under consideration are compared with this base case or default path.
4. **Develop cost estimate for each alternative.** The cost estimate for each alternative includes all life-cycle costs from pre-construction through decommissioning and salvage (if applicable). It should include other quantifiable costs, whether direct or indirect.
5. **Identify quantifiable and non-quantifiable benefits.** Each alternative is expected to yield benefits. When planning and designing for natural hazards, benefits are usually quantified in terms of losses avoided, that is, damage or interruptions to service that would normally result if the alternative was not implemented (or the damage did not occur because of prevention). Losses avoided are quantified in dollars. Some benefits are difficult to quantify but contribute positively to the project, for example, improved aesthetics, better health, or business continuity. These benefits are noted in the analysis and included as placeholders when dollar values are not available or have not been estimated.
6. **Define selection criteria for alternatives.** The agency (and sometimes the public) needs to determine the bases on which the alternatives will be compared and the decision will be made, sometimes adding further consideration of what is at stake. CBA might be the only criterion, or it might be one of many criteria. Further, CBA itself has different metrics that can be used

to evaluate among alternatives. The CBA metric used for selection will depend on the agency's priorities or means of doing business (metrics are discussed further in the sections that follow).

7. **Compare alternatives.** Using the selection criteria established by the agency, each alternative should be evaluated and compared against the others being considered. Common CBA metrics used for comparison include benefit-cost ratio, net present value, and return on investment. At this point, sensitivity analysis may be performed to evaluate how a change in assumptions could affect the CBA.
8. **Report results and recommendations.** The results of the analysis are summarized and conclusions are presented. The conclusions should tie back to the CBA and any other evaluation criteria used to recommend the preferred alternative, any rankings of alternatives, or both.

The total quantifiable and non-quantifiable value of the benefits needs to balance or outweigh that of the costs for the project to be considered cost-effective.

Cost-Benefit Analysis Metrics

To compare different projects or alternatives of the same project in which costs and benefits may occur in different years, discounting is used to convert future benefits and costs to a current-year perspective. One of the most frequently used metrics used when deciding whether a project can be justified is the net present value (NPV). The NPV is the discounted monetized value of expected net benefits (i.e., benefits minus costs). As discussed below, metrics (such as the discount rate, internal rate of return, simple payback period, discounted payback period, net present value, benefit-cost ratio, or return on investment) can be used to summarize CBA results.

Discount Rate

In our culture, people, agencies, and businesses often prefer to have benefits immediately and delay costs. As a result, people value future benefits less than they do immediate flows of money. To reconcile this when comparing different projects or alternatives of the same project that may have costs and benefits occurring in different years, discounting is used to convert future benefits and costs to a current-year perspective. Discounting involves the use of a **discount rate**—the annual percentage change in the present value of a future dollar. The formula for calculating the present value (PV) of a future value is given by Equation 1.

Equation 1. Present value formula.

$$PV = \frac{V}{(1+r)^t}$$

where

V = is a value (positive or negative) occurring at t,
t = a given period of time, and
r = is the discount rate (e.g., $r = 7\% = 0.07$)

Using this formula shows that the choice of discount rate (r) plays a large role in a CBA; a lower discount rate generates a higher present value to future flows than does a higher discount rate. For example, a $1,000 benefit that occurs in 30 years is equivalent to $231 today at a 5 percent discount rate, but only $131 using a 7 percent discount rate.

There are two types of discount rate: (1) the financial discount rate and (2) the social discount rate.

1. The **financial discount rate**, also known as the private discount rate, is the interest or borrowing rate, or the weighted average cost of capital for a project. In the United States, a financial

discount rate of 7 percent has been used for federally financed projects. At one time this was conservative—it meant more public investment or service now. However, when public costs caused by climate change and increasing impacts are inadequately valued and evaluated now, owing to prevalent financial discount rates, 7 percent is neither conservative nor protective of the public interest. A rate of 10 percent or greater might be used for privately funded projects to reflect opportunity cost in private markets.

2. The **social discount rate** is used in the sustainable net present value (S-NPV) analysis. The social discount rate can be thought of as valuing the present over the future by measuring a time preference for the present over the future and an opportunity cost based on finance and investment; that is, using resources today means that they are not invested to deliver a return elsewhere. The time preference can also be thought of as being composed of a pure time preference and a premium for the uncertainty that benefits and costs will materialize in the future. In the United States, the typical social discount rate is 7 percent, with a sensitivity analysis also run using 3 percent.

Economists have extensively debated the discount rate to use for climate change adaptation benefits because of the preference for and valuing of the current generation over future generations and their well-being. Climate change, future concentrations of carbon dioxide (CO_2) in the atmosphere, and impacts on average world temperature are highly certain, drawing agreement from over 99 percent of scientists now (and with increasing certainty since the dynamic was discovered in the 1800s). Also factoring into the debate is the idea that future generations will benefit the most from climate policies implemented today, and possibly a hope that the current generation and decision makers could evade associated costs for now. There has been uncertainty around the action that can or needs to be taken and its worth, a question that could be tackled with CBA; however, this has not been undertaken for transportation infrastructure in the United States.

Long-term uncertainty and discounting over long time horizons imply lower interest rates, often referred to as *intergenerational discounting* or *discounting future generations*. Researchers have generally concluded that discount rates of 1.4 percent to 4.3 percent are likely to be appropriate (Goulder and Williams, 2012). The Office of Management and Budget (OMB) recommends that sensitivity analyses be performed using both 3 percent and 7 percent discount rates. Meanwhile, in 2017 the TRB updated its study on the social cost of carbon; the Interagency Working Group on the Social Cost of Greenhouse Gases recommends conducting sensitivity analysis for carbon emissions using a lower bound of 2.5 percent and an upper bound of 5.0 percent, along with a 3.0 percent central rate to reflect uncertainty associated with climate change and future economic growth, as well as with the long time frames and intergenerational consequences associated with climate change. "The National Academies of Sciences and the U.S. Council of Economic Advisers strongly support a 3 percent or lower discount rate for intergenerational effects. A 7 percent rate based on private capital returns is considered inappropriate because the risk profiles of climate effects differ from private investments" (Revesz et al., 2017). Despite this, the current federal guidance is that CBAs use a 7 percent discount rate for carbon and non-carbon costs and benefits (with a 3 percent rate as a sensitivity analysis).

Additional information regarding discount rates is included in Appendix A.

Internal Rate of Return

Internal rate of return (IRR) is a measure of profitability or investment efficiency. IRR is a discount rate that makes the NPV of all cash flows from a particular project equal to zero. IRR may give better insights than return on investment in capital-constrained situations. However, when comparing mutually exclusive projects, NPV is the appropriate measure.

Table 1. Example simple payback period.

Year	1	2	3	4	5
Reduction in O&M	$2,000	$2,000	$2,000	$2,000	$2,000
Cumulative Reduction in O&M	$2,000	$4,000	$6,000	$8,000	**$10,000**

Simple Payback Period

Simple payback period is the number of years or months until capital is recouped by the flow of benefits or cash flow. The payback period is used to determine timing of the project or the length of time capital is at risk. A shorter payback period means less risk. The simple payback period uses undiscounted benefits or cash flows. In other words, the cash flows from the project are taken at their nominal value to determine the time until the project pays back. For this reason, the simple payback period is usually shorter than the discounted payback period (discussed in the following section).

For example, a project to install five 100-square-foot bioswales will cost $10,000. It is anticipated that installing these green infrastructure drainage improvements would reduce operations and maintenance (O&M) costs for the adjacent parking lot by $2,000 per year. The simple payback period is 5 years, as shown in Table 1.

Discounted Payback Period

Discounted payback period is the number of years or months until capital is recouped by the flow of benefits or cash flow. The payback period is used to determine timing of the project or the length of time capital is at risk. A shorter payback means less risk. The discounted payback period uses discounted benefits or cash flows. In other words, the cash flows from the project are discounted by the discount rate before the payback period is determined. For this reason, the discounted payback period is usually longer than the simple payback period (discussed previously).

For example, assume that the bioswale project, which the owner is considering to be a green infrastructure/environmental project, is discounted at a rate of 3 percent. Calculating the present value interest factors using Equation 1, the discounted payback is between 5 and 6 years, as shown in Table 2.

Net Present Value

OMB Circular A-94 (1992, 2016) states that CBAs should be prepared on a **net present value** basis. NPV measures the present-day value of benefits less the present-day value of costs, meaning the present value of benefits gained from the project is compared with the total project cost to evaluate cost-effectiveness. Because the value of money changes over time, it is useful to calculate the monetary values of costs and benefits of a proposed project in today's dollars (or dollars of a particular date) so that they can be more easily and accurately compared. This is done using a discount rate, which is the rate of return for the project. NPV is calculated by

Table 2. Example discounted payback period.

Year	1	2	3	4	5	6
Reduction in O&M	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
Present Value Interest Factor	0.971	0.943	0.915	0.888	0.863	0.837
Discounted Reduction in O&M	$1,942	$1,886	$1,830	$1,776	$1,726	$1,674
Cumulative Reduction in O&M	$1,942	$3,828	$5,658	$7,434	$9,160	**$10,834**

discounting cash flows over time using the discount rate and summing the discounted values. This metric allows the time value of money to be taken into account because cash flows further into the future become more discounted.

Because project benefits accumulate over time, project benefits are calculated on an average annual basis ("annualized") and then multiplied by a present value coefficient (PVC) to determine the present value of the benefits. As shown in Equation 2, the PVC is a product of the estimated useful life of the project and the discount rate.

Equation 2. Present value coefficient (PVC) formula.

$$PVC = \frac{\left[1-(1+r)^{-T}\right]}{r}$$

where

PVC= present value coefficient
r = discount rate
T = project useful life (years)

Present value coefficients for several interest rates and time periods are included in Appendix B.

NPV is used in go/no go or whether-to-proceed decisions. It is a measure of worth or value. An NPV greater than 0 means the project is economically efficient. Projects or alternatives can be ranked in terms of NPV.

Benefit-Cost Ratio

Benefit-cost ratio (BCR) is the present value of benefits divided by present value of costs. The BCR is used in go/no go, whether-to-proceed decisions. It indicates dollars of benefit per dollar of cost. A ratio greater than 1 means the project is worthwhile.

Return on Investment

Return on investment (ROI) is the benefit to the project from the investment of resources (Equation 3).

Equation 3. Return on investment calculation.

$$ROI = \frac{Profit, Gain, or\ Benefit\ Investment - Cost\ of\ Investment}{Cost\ of\ Investment}$$

As a performance measure, ROI is used to evaluate the efficiency of an investment or investments, or how efficiently the investment is used.

Different metrics can allow decision makers to apply their own selection criteria to the data to make a decision. For example, assume a DOT is trying to choose between three alternatives (data in Table 3 are hypothetical and for illustrative purposes only):

Table 3. Example data for application of selection criteria and CBA metrics.

Alternative	Cost	Benefit	NPV	BCR	ROI
A	$100	$130	$30	1.3	0.3
B	$250	$500	$250	2.0	1.0
C	$500	$800	$300	1.6	0.6

The DOT might have different criteria for making its decision about which alternative to pursue:

- A budget-constrained agency might want to limit the first cost to accommodate low available capital. In this case, the agency would select Alternative A, as it has the lowest initial cost.
- An agency interested in determining the greatest benefit for dollars spent would be most interested in the BCR. In this case, the agency would select Alternative B, as its BCR of 2.0 is higher than the other two alternatives.
- An agency interested in maximizing its benefits could select Alternative C, which has the highest NPV of benefits.
- Assuming that the periods of the alternatives are the same, an agency interested in maximizing its ROI would select Alternative B. However, if the payback period of Alternative B is 3 years, the average annual return for Alternative B is 1.0/3, or 0.33, in which case Alternative C has a higher average annual ROI and would be selected.

Different Types of Cost-Benefit Analysis

Project Cost-Benefit Analysis

A project CBA evaluates the financial feasibility of a project, focusing on the benefits and costs to the project without considering the impacts to the local, state, or regional economy or the economy as a whole. A financial CBA can be conducted in constant (i.e., present value) or current dollars. This is the most commonly conducted type of CBA.

Life-Cycle Cost Analysis

Life-cycle cost analysis (LCCA) is a subset of CBA. LCCA compares the total user and agency costs of different options over a period when the alternatives are being compared. This CBA includes the capital costs, operations and maintenance, replacement costs, residual value, and disposal costs of an asset. Typically, LCCA assumes that an asset is maintained proactively according to an established schedule, rather than reactively. LCCA is conducted in constant dollars and quantifies only the financial costs associated with an asset. FHWA has an LCCA primer, which is available from https://www.fhwa.dot.gov/asset/lcca/010621.pdf.

Return on Investment Analysis

An ROI analysis differs from a CBA in that ROI is calculated using the most tangible costs and benefits, whereas CBA is more detailed than ROI and includes intangibles such as the value of a person's time or state of health.

Triple Bottom-Line Analysis and Triple Bottom-Line Cost-Benefit Analysis

Triple bottom-line (TBL) analysis evaluates a project or policy based on its combined financial, environmental, and social impacts. The financial (or profits) impacts are the life-cycle costs associated with the project; LCCA can be used as the financial cost analysis in a TBL analysis. The environmental (or planet) impacts are the effects of a project on the surrounding environment, habitat, or climate. The social (or people) impacts are the effects of a project on the broader community, quality of life, or society. These three values presented together form the TBL evaluation and are typically represented as Profits, Planet, and People. They can be used in the context of a CBA by quantifying the monetary values associated with each in constant dollars and adding them up to measure the TBL in dollars. Multiple interest rates might be used to reflect the different time frames associated with economic, social, and environmental benefits (see Appendix A for more detailed information about interest rate selection).

Sustainable Return on Investment

Sustainable return on investment (**S-ROI**) is an enhanced form of CBA that includes probabilistic assessment and stakeholder engagement. This framework takes into account the entire scope of risk-adjusted costs and benefits related to sustainable design, including traditional internal cash impacts such as savings on energy or water costs, as well as all other appropriate internal and external non-cash impacts such as the dollar value of environmental savings from reduced potable water use or air emissions. The analysis results in at least two sets of output metrics in terms of probabilities, one from the perspective of the organization on a cash flow basis and the other from the perspective of society, which would include the value of externalities such as health and safety benefits expressed in dollars. Finally, the analysis needs to allow for transparency and incorporate a process for expert and stakeholder opinion on the model structure and inputs. S-ROI is a form of TBL-CBA.

Economic Impact Analysis

Economic impact analysis (**EIA**) considers the effects that an action, policy, or project has on the economic development of a community or region. Direct (from project expenditures), indirect (from project suppliers' expenditures), and induced (from those affected spending their wages) impacts can be estimated from input-output tables of the economy and used to evaluate the impacts on economic variables such as employment, tax revenue, and property values. The indirect effects considered in an EIA are not part of a traditional CBA.

Funding Sources and Their Impact on Analysis

Capital Budget

The capital budget is derived from public funds—paid for by the public in the form of taxes. The capital budget is built through a combination of federal transfers, state taxes and fees, and other revenues. Transportation spending represents 8.1 percent of total state spending; by comparison, 29.0 percent of state funds are dedicated to Medicaid, and 19.4 percent to K–12 education (NASBO, 2017). Spending in transportation from states' own funds grew 8.8 percent and 6.7 percent in FY 2015 and FY 2016, respectively. Table 4 shows the breakout of revenue sources for U.S. transportation projects in FY 2016.

Public entities care about the welfare of future generations; essentially, decisions have to serve current as well as future generations. Public agencies guard public welfare and steward common

Table 4. State expenditure for transportation by fund source in FY 2016 (NASBO, 2017).

Revenue Source	Portion of Total Transportation Spending
State gasoline taxes, etc. (earmarked revenue sources)	58.7%
Federal funds	29.2%
Bonds	8.0%
General funds	4.1%

resources and long-term public infrastructure. Public right-of-way, road bases, and so on are also long-term public investments. Consequently, projects funded as part of a transportation agency's capital budget tend to have longer time horizons for planning and implementation, sometimes lasting centuries. They also usually have a lower discount rate to reflect their long-term outlook (i.e., the social discount rate). Using a lower discount rate means that future costs and benefits are given a higher present value (more equal with achievement of the same benefits for those here today) than if they were discounted using a higher rate (in which case they may be discounted massively to the extent they are not counted at all). Because the projects are funded from the available (and future) budget, no loans are being used to finance them, which means there are no monthly or annual debt payments. This lowers the annual costs, which helps to make projects more favorable in a CBA than projects that use other financing mechanisms, if such considerations are taken into account. Because government agencies have a social obligation to fulfill, they aim to evaluate projects based on their value to the public without discriminating against some people, such as those of different times or those who are unable to vote, and considering both positive and negative externalities.

Loans, Grants, and Other Financing

Issuing debt is common practice among states to fill funding gaps in infrastructure spending. In a recent survey, 36 of the 42 states that responded (86 percent) report having outstanding debt obligations for transportation purposes, and 95 percent of states report the authority to issue debt for such purposes (Henkin and DeMoore, 2017).

> State debt issuance takes many forms, such as general obligation bonds, revenue bonds, project finance such as toll revenue bonds, and a variety of other federal and state debt mechanisms. Each form of debt has a different credit profile and thus a potentially different debt management approach. For example, project finance debt such as toll revenue bonds can be nonrecourse or limited recourse to other resources of the issuing entity. In such financings, the debt is repaid from the cash flow generated by the project. With general obligation or tax-backed bonds, the success of the project may not be tied to the ability to repay the debt. (Henkin and DeMoore, 2017)

Bonds

Bonds are a common way to issue debt. For reference, a bond is a way for an entity to raise money to finance projects. Instead of borrowing from a bank, an entity can issue bonds that investors "buy" for a defined period (defined by the bond's maturity date) with a fixed interest rate ("coupon"). Each year, the borrower pays interest, and at the maturity date pays back the loaned funds (principal) (Investopedia, 2003).

The city, county, or state is the borrower for tax-exempt municipal bonds, or "muni bonds." As these bonds are tax exempt, they are an attractive, low-risk investment. They come in two forms: (1) tax-backed, also known as general obligation bonds, and (2) revenue-backed, which dictate how the municipality pays back the interest and principal. A tax-backed bond is backed by the taxing power of the issuing city, county, or state, and is paid back using property (and other applicable) taxes. An example of a revenue-backed bond is issuing a bond to improve a water treatment plant then using revenue from customer water bills to operate and maintain the system, as well as pay back the bond (Edward Jones, 2017).

Green bonds may be a way to fill the funding gap while still fulfilling environmental goals. A green bond is a tax-exempt bond earmarked toward funding projects that generate positive environmental or climate impacts, such as energy efficiency, sustainable agriculture, clean transportation, and sustainable water management. Because of their tax-exempt status, green bonds offer a financial advantage over traditional bonds, providing an incentive to tackle sustainability issues. In 2012, green bond issuance accounted for $2.6 billion but rose to $157 billion in 2019

(Investopedia, 2020). Green bonds are also attractive to issuers, as they offer liquidity and access to funding that was previously not possible.

The Transportation Infrastructure Finance and Innovation Act

The Transportation Infrastructure Finance and Innovation Act (TIFIA) is another way for DOTs to fill the funding gap. This federal program administered by the U.S. DOT provides credit assistance in the form of loans, loan guarantees, and standby credit lines for qualified large-scale surface transportation projects (U.S. DOT, 2014). In so doing, U.S. DOT helps attract private and non-federal co-investments for state and local governments unable to obtain financing at reasonable rates.

Loans and Grants and Cost-Benefit Analysis

In the case of most transportation projects, loans taken on by public entities provide funding for infrastructure. Unlike with the capital budget, instead of using current available funds, governments borrow to fund projects. Depending on the financial stability of the public entity in question, governments can typically secure long-term loans at favorable rates because the loan is guaranteed by the state.

Grants issued by federal agencies also provide funds for infrastructure, and thus are using public funds to finance transportation projects. One of the most well-known annual grant programs was the Transportation Investment Generating Economic Recovery (TIGER) program, which was active through FY 2017. It was replaced in FY 2018 by the Better Utilizing Investments to Leverage Development (BUILD) transportation discretionary grants program.

FHWA Emergency Relief and FEMA Recovery Grants

Transportation agencies can often access post-disaster programs such as FHWA's Emergency Relief (ER) program after severe storms or impacts. This program provides 80 to 90 percent of funds required to repair disaster-damaged federal aid roads. Typically, FHWA ER funds are used to restore the damaged facility to its pre-disaster condition; however, some "betterments" may be allowable if they will reduce the risk of future damage; the FHWA division office must determine that doing so would be cost-effective. Cost-effectiveness analysis of betterments under the ER program differs from typical CBA in that it does not include factors such as traffic delay costs, added user costs, motorist safety, and so on; it includes only the cost of the protective features or changes that modify the function or character of the facility before the disaster or catastrophic failure. After a federally declared disaster, FEMA may provide funding for roads ineligible for FHWA ER funding. FEMA funding typically ranges from 75 to 90 percent of the funds required to repair damaged facilities. FEMA-funded projects may be eligible for betterments, called 406 mitigation measures, as part of the Public Assistance program, provided the measures meet FEMA CBA requirements.

Regardless of whether the project is being funded entirely by loans or partially with grants supplemented by loans, the funding for recovery from extreme weather events or climate impacts is still provided by the public. Thus, the discount rate will be low, emphasizing the more equitable intergenerational value of money, as well as the public sector's lower opportunity cost of capital. Given that a loan is essentially substituting future expenditure for current expenditure, there is still an implied bias toward present consumption.

Public-Private Partnerships

Governments often partner with private entities to help design, deliver, and operate transportation projects. Whereas governments have a social contract, companies have an obligation to optimize their bottom line. Public-private partnerships (P3s) are contracts between public agencies and private entities that enable greater private sector responsibility for a transportation project, including in design, delivery, financing, operation, and maintenance, beyond traditional design–bid–build procurements (Parsons Brinckerhoff et al., 2015). The degree to which the private sector assumes responsibility, including financial risk, differs from project to project. There are numerous P3 agreements, such as design–build, design–build–finance, design–build–finance–operate, and design–build–finance–operate–maintain (Parsons Brinckerhoff et al., 2015). DOTs are increasingly looking to P3s as a means of financing projects; as of February 2018, 28 U.S. highway P3s will have achieved financial close, with 20 occurring in the last 10 years (FHWA, 2017).

Despite more research showing the financial benefits of socially focused business, firms have a mandate to maximize profits. As a result, their priorities are not the same as the public sector and its long-term asset management, including the welfare of future generations. Private firms reinvest profit to make more money now, rather than holding these long-term social welfare responsibilities. Thus, their work and estimates use a higher discount rate than governments, as use of NPV can wipe out the value of future generations, their needs, or longer-term stewardship of public assets. Although a public entity is involved in a project, private involvement adds upward pressure to the discount rate, which DOTs then have to cope with. Some DOTs have dealt with this in creative ways, such as the Hooksett Rest Stop project in New Hampshire (Box 1).

Private Funding

Private sources of funding, such as from pension funds or sovereign wealth funds, have grown in importance in the last decade. Public infrastructure is now seen as an attractive, low-risk investment for private funds simply because people need to travel (Podkul, 2011). Transportation agencies borrowing against or liquidating transportation infrastructure to pay for maintenance or operations needs is akin to selling a house to cover home expenses not met by income (in this case, taxes). Jean-Paul Rodrigue (2017) raises arguments that have been used to pressure public officials to consider privatizing transport infrastructure:

1. **Fiscal burden.** Governments can no longer afford transportation infrastructure maintenance and upgrades as other budget demands take priority.
2. **High operating costs.** With their orientation to maximize profits for shareholders, private interests better control technical and financial risks.
3. **Cross subsidies.** Much of state transportation spending is cross-subsidized through fuel taxes and so on. If private finances can be tapped to purchase public assets and operate the system, this frees up state revenue to be spent elsewhere or to reduce taxes.
4. **Equalization.** With public funds, people want their fair share of the benefits. If a project is built in one region, another region expects similar levels of funding, even if it is not efficient or would not maximize public benefit according to certain standards, thus increasing the cost of public provision. Privately financed infrastructure does not face the burden of public accountability or expectations.

Three forms of privately funded infrastructure are described briefly as follows:

1. **Sale or concession agreement.** Owing to budgetary limitations, a government may be forced to sell or lease its assets. For a concession agreement, this commonly takes the form of a long-term lease requiring that the concessionaire maintain, upgrade, and build infrastructure and equipment to certain minimum levels.
2. **Concessions for new projects.** By offering tax breaks for new projects, governments ensure that existing assets remain untouched, and managerial expertise and technical know-how are employed.
3. **Management contract.** While ownership remains public, management is given to a private operator, commonly through a bidding process.

Box 1. Hooksett Rest Stop: A Successful Public-Private Partnership in New Hampshire

Interstate 93 in New Hampshire serves as a main thoroughfare between Boston, the White Mountains, and Lake Winnipesaukee, where many visitors enjoy the natural beauty and outdoor activities of the area. The town of Hooksett, located between Manchester and Concord, is the mid-point between Boston, the mountains, and the lake. Through a public-private partnership, the Hooksett rest area, first constructed in 1977, was transformed from its original state into a vibrant destination in itself (Figure 4). The northbound and southbound rest areas feature not only fuel stations and restrooms, but also an information center, a general store with camping supplies, a League of New Hampshire Craftsmen store, a bank (northbound location only), and a Common Man food court that includes a 1950s-style diner, an Italian restaurant, a country deli, and a bakery/coffee shop. A liquor and wine outlet operated by the State Liquor Commission is also at each rest stop.

A private developer worked with the state DOT to create the New Hampshire–centric rest areas; the developer incurred the costs of the project and agreed to a cost share of the revenues with the state. Sales have been much higher than forecasted during the first year of operation, bringing in tens of millions of dollars and prompting the New Hampshire DOT to consider a similar approach for several other projects.

Figure 4. Architectural rendering of the Hooksett Rest Area (courtesy of New Hampshire DOT and used with permission).

Unlike in a P3, if there is no public entity to dilute the upward pressure on the discount rate, the privately funded project will have the highest discount rate out of all the options and future costs and benefits will not be given much or any weight in a present value calculation. There is more of an incentive to reduce costs now to maximize short-term benefits, rather than focusing on reducing costs that are unaccounted for or externalized in most financial transactions, or increasing benefits to future generations since externalities typically do not affect the bottom

Figure 5. Impacts of different financing types on CBA. Green indicates more favorable and red is less favorable.

line (unless externalities such as pollution are internalized by giving them a market price or tax). Even though private investment derives from sources such as pension funds and other entities that have long-term financial strategies, the time horizon for project planning and implementation is likely to be shorter than for government-financed projects. Consequently, the focus is on projects that have smaller up-front costs or projects that generate benefits immediately, enabling investors to recoup the initial investment quickly.

Overall Impact of Financing on Cost-Benefit Analysis

Figure 5 offers a quick overview of how each financing option treats the characteristics on which impact on the CBA is based. Green indicates a favorable impact on an overall value for money analysis—that is, a full CBA—whereas red indicates a potentially less-favorable impact.

Update to the Scenario

Virginia DOT leadership has determined that cost-benefit analysis will be one of the criteria used to determine if climate and extreme weather adaptation measures should be incorporated into the design for the replacement culvert. Net present value and benefit-cost ratio will be used to do the initial evaluation of adaptation alternatives once they are identified. If one alternative has a greater NPV while another has a higher benefit-cost ratio, the alternative with the higher NPV will be selected as the recommended alternative.

For federal funding purposes, one of the rates calculated will be the OMB A-94 prescribed discount rate of 7 percent for most costs. A sensitivity analysis of the project will be performed using a 3 percent discount rate in place of the 7 percent rate for comparison purposes.

Data needed at this stage include

- Discount rates to be used in the analysis and
- Source of funding for the project (optional—needed if including cost of capital in analysis).

CHAPTER 3

Climate Considerations

Models and Scenarios

Climate science has made significant advancements in the past couple of decades in the ability to model complex interactions occurring between dynamic factors. Global models, called general circulation models (GCMs), help explain at a high level the interactions between the atmosphere, the earth, and the ocean. Because greenhouse gas (GHG) emissions, particularly CO_2, influence the models, they are an important part of each GCM. Scenarios downscaled to reflect regional conditions are input into the GCMs to predict future conditions for specific geographies at different points in the future. The scenarios have been developed by the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP) (Box 2).

Box 2. What Is a Coupled Model Intercomparison Project?

In support of the Intergovernmental Panel on Climate Change's (IPCC's) Assessment Report updates, the World Climate Research Programme created the Coupled Model Intercomparison Project (CMIP) in 1995 to study how changes in climate variables, such as the amount of CO_2 in the atmosphere, result in changes to the climate in mathematical models. Assumptions about future GHG levels inform the scenarios used in CMIP3 (2007) and the trajectories used in CMIP5 (2014).

CMIP3, which was used as the basis for the IPCC's 4th Assessment Report in 2007, uses scenarios developed for the Special Report on Emissions Scenarios (SRES). The SRES assumes that changes in future emissions stem from changes in driving forces such as demographics, economic development, and technology. CMIP3 establishes four storylines that describe the relationships between emissions and their driving forces. Scenarios are derived from the storylines to project potential futures. Three storylines and scenarios are used frequently:

1. **B1.** This storyline is the most optimistic. It assumes that the world consistently chooses a development path that favors the efficient use of resources to support economic growth. Specifically, it assumes rapid social development and increases in education levels, high economic growth worldwide, a comparatively small increase in energy use, and a timely shift to non-fossil fuels.

(continued on next page)

Box 2. (Continued)

2. **A1B.** This is a scenario characterized by two different storylines and is generally viewed as moderate to optimistic. It assumes rapid population growth to the mid-21st century that then slowly decreases, rapid introduction of new technologies, and a balanced use of fossil and non-fossil fuels.
3. **A2.** This is the current business–as-usual path and assumes continuation in the future. Specifically, population growth continues at its current rate, regional patterns change little, and current economic development patterns change little. Transportation and electricity remain primarily powered by fossil fuels. Slow adoption of alternative fuel sources continues.

A summary of the CO_2 emissions assumed into the future for the various storylines in CMIP3 is shown in Figure 6.

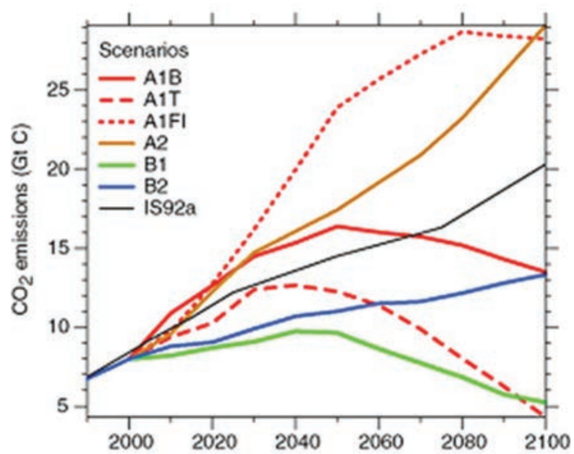

Figure 6. CMIP3 CO_2 emissions scenarios (IPCC, 2001).

CMIP5 is the most current and extensive of the CMIPs. It uses representative concentration pathways (RCPs) in place of storylines and scenarios (i.e., SRES) to estimate future GHG concentrations in the atmosphere. There are four RCPs named after a possible range of radiative forcing values in the year 2100:

1. **2.6.** Atmospheric GHG concentrations peak at 2.6 watts per square meter (W/m^2) before 2100 and then begin to decline
2. **4.5.** GHG concentrations stabilize at 4.5 W/m^2 before 2100 and then begin to decline. Similar to B1 storyline in CMIP3.
3. **6.0.** GHG concentrations stabilize at 6.0 W/m^2 before 2100 and then begin to decline. Similar to B2 storyline in CMIP3.
4. **8.5.** GHG concentrations reach 8.5 W/m^2 by 2100. Similar to A1F1 scenario in CMIP3.

Box 2. (Continued)

A summary of the radiative forcings over time for the CMIP5 RCPs is shown in Figure 7.

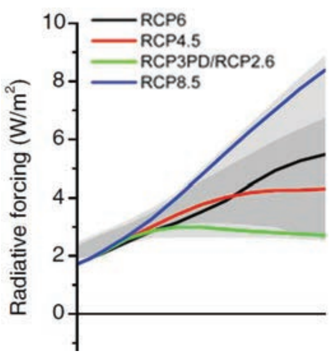

Figure 7. CMIP5 CO_2 emissions scenarios (van Vuuren et al., 2011).

The emissions from CMIP3 and the radiative forcings for CMIP5 have been converted to CO_2 concentrations. Figure 8 compares the CO_2 concentrations under the CMIP3 SRES with those from the CMIP5 RCPs.

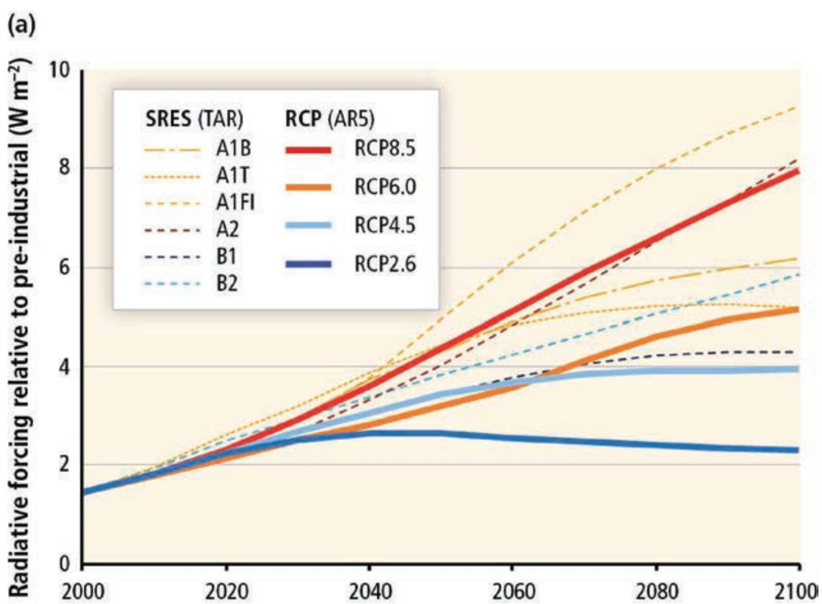

Figure 8. Comparison of CMIP3 and CMIP5 emissions scenarios (IPCC, Figure 1-4, 2014).

Climate scientists use multiple consensus-based scenarios illustrating a spectrum of modeled changes in climate and weather over the 21st century, so selecting the appropriate climate scenarios is necessary to arrive at a useful CBA (Figure 9). What is considered an appropriate scenario may vary depending on many factors. Some states require consideration of a particular scenario or provide guidance about when to choose which scenario. The Massachusetts Department of Transportation (2017) has published statewide maps in which representative concentration pathways (RCPs) 4.5, 6.0, and 8.5 for four future periods (2030, 2050, 2070, and 2100) are developed for

- The projected percentage change of the 1 percent annual exceedance probability 24-hour precipitation event,
- The projected 1 percent annual exceedance probability 24-hour precipitation depth,
- The projected annual maximum number of consecutive days with temperatures over 95°F, and
- The projected number of days with temperatures over 95°F in the summer (https://gis.massdot.state.ma.us/cpws/).

These maps allow planners to see and consider several planning scenarios over the short and long terms. Not all states have developed climate-planning scenarios; in these cases, transportation agencies may be left to make their own determinations of which scenarios are appropriate. Until the United States departs from a business-as-usual path, an argument can be made that RCP 8.5 is the path to use in calculations, but as discussed in the following section, additional factors such as time frames for implementation, service life, and geographic context need to be considered as well when selecting a planning scenario.

Some government agencies are starting to move away from the use of probabilistic scenarios toward non-probabilistic scenarios to manage uncertainty. For example, the Department of Defense and the National Park Service are starting to advocate the use of "what-if" scenarios for planning purposes. Under this approach, a planner asks questions such as

- What if extreme rain events increase surface water runoff flows by 100 cubic feet per second (cfs) per event in the next 20 years? How will that affect my culvert? What adaptation measures will we consider?
- What if extreme rain events increase surface water runoff flows by 1,000 cfs per event in the next 20 years? How will that affect my culvert? What adaptation measures will we consider?

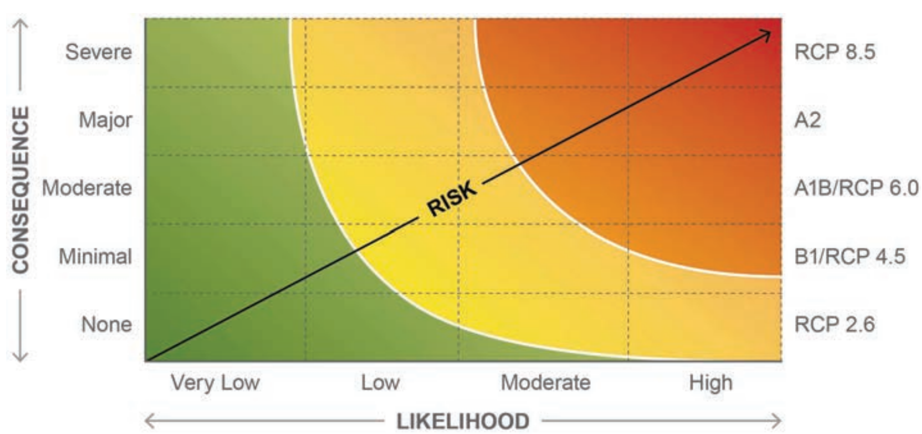

Figure 9. The selection of a climate scenario for planning will depend on the likelihood of occurrence and the severity of the consequences if the event occurs.

Non-probabilistic scenarios allow planners to ask questions based in probabilistic climate projections without relying on a specific SRES or RCP so that they can better manage risk. Planners can then focus on the risk issues at stake rather than bring in climate change and the path under way. This approach helps planners and others involved to consider the impacts of climate change at the local level "in the context of physical, social, political, environmental, operational, and economic variables that strongly influence decision making" (NPS, 2013).

The Maine Department of Transportation (MaineDOT) used non-probabilistic scenarios for its FHWA adaptation pilot. The department selected three modeled scenarios based on inundation maps—no sea level rise, 3.3 feet of sea level rise (moderate projection), and 6.0 feet of sea level rise (business-as-usual projection)—and developed adaptation options for two bridges and one culvert, to which it then applied depth-damage functions to estimate construction costs, damage and repair costs, and life-cycle costs (MaineDOT, 2014).

If a DOT has not received guidance regarding climate scenarios to use in planning, a sensible approach is to consider relevant asset characteristics such as location (vulnerability and criticality), desired service life, capital and repair costs, and risk tolerance. Depending on these characteristics, the scenarios selected for CBA at the project level could vary from those that informed a climate vulnerability assessment of the entire asset catalogue. For example, vulnerable infrastructure with higher criticality may benefit from being resilient to current path projections and the business-as-usual/upper end of climate scenarios. It also makes sense to consider investing in greater resilience for assets with longer service lives, though resilience of the area served is also a consideration. If the surrounding area has become unlivable, that is a factor.

The scenarios and time frames selected will have bearing on which alternatives are considered adaptive, their overall cost, and estimation of losses avoided. Ultimately, CBA will help distinguish which alternatives are preferred based on performance over the range of time frames and scenarios examined.

Considering Changing Climate in a Proposed Design

Engineering design practice through much of the last century was to design for climatic phenomena, such as site hydrology and hydraulics, based on the assumption that the past accurately represented the future. Climate scientists refer to this assumption as *stationarity*, defined as unchanging mean, variance, and so on in climate-influenced design characteristics. If the past and future are similar, this assumption is reasonable, but even within the past 50 years many U.S. regions have seen changes that are significant for project design. In other words, stationarity can no longer be assumed. For example, from 1958 to 2012, the Northeast experienced a 71 percent increase in the amount of precipitation falling in very heavy events (Figure 10), in which "very heavy events" are defined as "the heaviest 1 percent of all daily events" (USGCRP, 2014). Furthermore, the RCPs project that the frequency of extreme daily precipitation events in the Northeast will continue to increase on the business-as-usual path (extreme high) and in the extreme low scenarios (Figure 11), in which "extreme daily precipitation events" are defined as "a daily amount that now occurs once in 20 years" (USGCRP, 2014). Additional information regarding climate models and non-stationarity is included in Appendix C.

Yet, many of the resources that constrain projects, such as design manuals and federal funding guidelines, assume stationarity. As a consequence, these resources have been slow to incorporate both observed changes in design storms and projected changes based on climate models, leaving agency engineers with limited guidance and support for resilient engineering design efforts. Further, precipitation events as defined by climate scientists, for example, very heavy and extreme, do not correlate well to engineering design parameters, making design for future conditions challenging under non-stationarity.

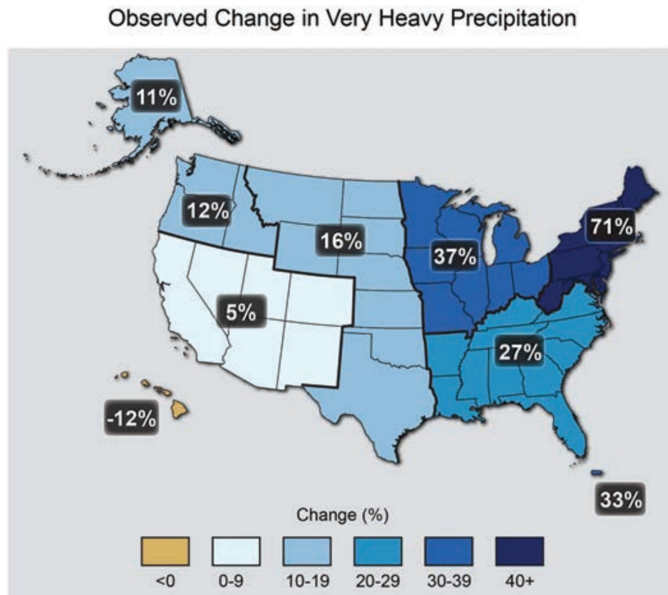

Figure 10. The number of very heavy rainfall events increased throughout most of the United States from 1958 to 2012 (USGCRP, 2014, Figure 2.18).

FHWA has undertaken research to evaluate non-stationarity and associated potential impacts on transportation infrastructure, in particular through its Gulf Coast studies and climate-resilience pilot studies. These studies have enabled FHWA to identify different asset types' sensitivities to various climate stressors. A consolidated summary of some road network–related assets and stressors is summarized in Table 5. The full table is available at https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/phasmod_task4/index.cfm. Additional information regarding the vulnerability of certain transportation asset characteristics to climate change is summarized in Table 6. These studies and data can be used to inform the development of design guidelines to account for expected future climate conditions.

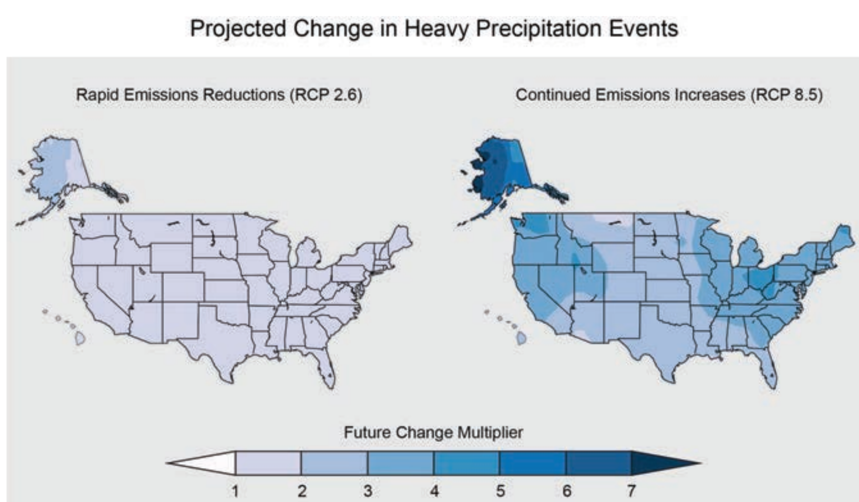

Figure 11. The frequency of extreme daily precipitation events is expected to continue to increase into the future under all emissions projections (USGCRP, 2014, Figure 2.19).

Table 5. Summary of sensitivities of transportation asset types to climate stressors (adapted from FHWA, 2013b).

	Paved Roads	Culverts	Bridges	Buildings
Extreme Heat	Sustained high temperatures can soften asphalt concrete pavement, resulting in rutting and shoving. Concrete pavement can heave at the joints. Thresholds for damage vary depending on pavement design; pavement binder may exhibit sensitivity starting at 108°F. While aggregate itself is not sensitive to temperature, its shape can influence the sensitivity of the overall hot-mix asphalt paving; angular aggregate may help prevent rutting.	No documented relationship.	Thermal expansion can expand road surfaces and bridge joints, increasing stresses on bridges. Research indicates that extreme heat results in temperature variations within girder sections, increasing stress in both tension and compression regions of the bridge (Hagedorn, 2016).	Greater needs for cooling and increased stress on air conditioning systems are possible. Demand for water and energy usage may also increase.
Precipi-tation-Driven Inland Flooding	The velocity of water flowing over roadways can cause pavement and embankment failures. Multiple instances of complete pavement submersion are likely to damage pavement over time. Heavy precipitation can infiltrate cracks and leak under the pavement, damaging the subgrade. Sensitivity of the pavement depends on design and traffic loads; thinner pavements are more sensitive to water, and higher traffic loads increase stress, which can cause deformation.	Heavy precipitation can cause debris accumulation, sedimentation, erosion, scour, piping, overflow, and conduit structural damage.	Increased flow velocities and depth beneath bridges can affect scour depth; if the stream elevation reaches the low chord bridge elevation, the local scour depths could be increased by 200%–300%. Overtopping can inundate the bridge, resulting in failure of the road surface (see Paved Roads column).	Flooding can inundate and damage buildings and building systems or components.

(continued on next page)

Table 5. (Continued).

	Paved Roads	Culverts	Bridges	Buildings
Sea Level Change	Hydraulically, sea level rise will reduce the 100-year return periods of flood-causing events because static water levels will be higher, so less rainfall and runoff will be required to achieve the same 100-year flood elevation (i.e., a smaller event will cause the same 100-year flooding). Tunnels may become more vulnerable both because the risk of their entrances and vents flooding will be greater and because the hydraulic pressure on the tunnel walls will increase as water tables rise. Combined with storm surge from hurricanes or nor'easters, gradual changes in sea level may be expected to damage or render inaccessible low-lying coastal roads and tunnels.	In low-lying coastal areas, tidal flooding likely will become more and more frequent. As sea level rises, drainage systems become less effective as the relative elevation of the system outlet to sea level surface elevation becomes closer, resulting in more flooding.	Sea level rise will decrease clearance under bridges. Combined with storm surge, sea level rise could increase erosion and scour damage to the abutment and cause slope failure.	Sea level rise in combination with tidal actions, subsidence, or both can inundate low-lying buildings and structures in coastal areas.
Storm Surge	Pavements exposed to overwash can be damaged by the direct wave attack on the seaward shoulder of the road, the water flow across the road and down the landward shoulder ("weir flow"), and the flow parallel to the road as the storm surge recedes and water settles on lower spots in the road. There is evidence that the "weir" flow might be the primary asset-failure type.	Storm surge can cause debris accumulation, sedimentation, erosion, scour, piping, inundation, and conduit structural damage.	Powerful storm waves can stress both the superstructure and the substructure of a bridge. Stress can damage or destroy the connection between the superstructure and the substructure, leading to the bridge span being shifted or even unseated completely. Shifting of the spans damages other parts of the bridge, including abutments, caps, and girders. Storm surge can also wash large debris, such as barges, into bridges, causing impact. Storm surge can also result in scour and erosion damage to the bridge.	Storm-surge forces acting directly on a building can cause it to collapse. Flooding from storm surge can inundate a building, damaging the building, its systems, and its contents. Erosion caused by storm surge can undermine foundations, resulting in structural damage and collapse. Storm surge can also carry debris, which can affect structures, causing damage.

Table 5. (Continued).

	Paved Roads	Culverts	Bridges	Buildings
Wind	Wind does not directly damage pavements, but can disrupt traffic.	Debris generated from a wind event can clog the stormwater drainage system, resulting in localized flooding.	Wind stresses bridges with horizontal loading. Strong winds can create high flow velocities and high wave impacts, which can stress the bridge superstructure and substructure, and can also lead to scour and erosion.	High winds can blow construction materials loose. Airborne debris can strike buildings and structures.
Drought	Drought can contribute to the cracking and splitting of pavement.	Sedimentation can occur during periods of low flow.	No documented relationship.	No documented relationship.
Dust Storms	No documented relationship, but can disrupt traffic.	No documented relationship, but could result in sediment deposition at the entrance to and within culverts.	Potential impact on mechanical and electrical systems used to operate the bridge.	No documented relationship, although could influence performance of mechanical systems.
Wildfire	Asphalt can ignite during tunnel fires. Research has shown that asphalt can ignite at temperatures between 896°F and 986°F, and degradation can begin at 572°F. Even without igniting pavement, high temperatures can soften it. Concrete is unlikely to ignite but can experience expansion around 1,112°F. Debris flows following wildfires can flood and damage roads.	Wildfires can denude slopes and change soil properties, affecting the watershed hydrology and sediment transport processes and increasing overland runoff. The increased runoff can lead to destructive debris flows, blocking and damaging culverts.	Post-wildfire debris flows can damage bridges via drag, buoyancy, impact, or burial. Bridges can be displaced, lifted off their foundations, or damaged from debris flow.	Buildings could burn.
Winter Storms	Issues are related primarily to freeze-thaw cycles. See Changes in Freeze/Thaw row.	Culverts can become blocked by snow and debris, resulting in localized flooding. Increased water flows around culverts can result in erosion around culverts.	Increased precipitation (snow or rain) can increase soil saturation, decreasing lateral soil resistance of piers and making the bridge susceptible to greater movement. Decreased incidents of winter storms could mean less use of salt deicers, which could decrease corrosion rates.	Excessive snow or ice loads can cause roof collapses. Ice infiltrating cracks in bricks and mortar or other exterior coatings can cause spalling. This moisture can also rot wood framing materials. The weight of snow and ice on trees and poles can topple them, damaging buildings and structures.

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30 Incorporating the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change—Guidebook

Table 5. (Continued).

	Paved Roads	Culverts	Bridges	Buildings
Changes in Freeze/ Thaw	Pavement reaction to freeze/thaw cycles depends on the paving mix (e.g., aggregate, air voids). Water seeps into cracks in the roadways, and during freeze/thaw cycles, the water freezes and expands, exerting pressure underneath the pavement surface. When the ice thaws, a void forms and vehicles driving over the pavement cause it to weaken and collapse over the void, forming potholes. This same phenomenon can cause cracks, deformations, and wheel ruts.	No documented relationship between freeze/thaw and metal culverts, although soil upthrust could result in displacement or loss of foundation support. Freeze/thaw could cause joint separation in concrete culverts.	Water that seeps into fissures in the bridge deck can result in cracking, eventually reaching the road surface. Concrete bridge components are also susceptible to freeze/thaw cracking. As temperatures increase, some geographies could experience an increase in freeze/thaw cycles, resulting in more damage to bridges than previously experienced when temperatures remained below freezing for long periods.	Increases in freeze/thaw will increase stresses to exterior coverings, possibly resulting in increased spalling of brick and delamination of roofing materials. Heave associated with freezing and subsequent re-settlement associated with thawing can crack concrete foundations.
Perma-frost Thaw	Permafrost is defined as any ground that remains frozen year-round for 2 or more consecutive years. As temperatures rise, the active layer of permafrost (the surface layer) becomes thicker, and the ice in the active layer melts. As the ice melts, the ground surface subsides, resulting in thaw settlement. This thaw settlement occurs unevenly, which can pose a threat to any infrastructure built on top of the permafrost.	Road slope sloughing can fill ditches and plug culverts with sediment. Permafrost thaw could weaken foundation soils, resulting in culvert settlement.	Bridge superstructures are not directly impacted by permafrost thaw. As global temperatures rise and permafrost begins to thaw, the pilings of bridges constructed on permafrost can settle, resulting in bridge collapse.	Permafrost thaw can undermine foundations, causing differential settlement and buildings sinking into the ground.

Table 6. Design or regulatory considerations regarding climate impacts on some transportation assets.

Topic	Design or Regulatory Considerations	Example Guidance
FEMA Floodplain	• Practical alternatives to locating within the floodplain for the 100-year event • Increases in the 100-year water surface elevation of an established regulatory floodway • Increases in the water surface outside the regulatory floodplain (less than 1.0 ft) and impact on additional property • Backwater limitations	• Title 23, Section 650, Subpart A: Location and Hydraulic Design of Encroachments on Flood Plains of the Code of Federal Regulations • FHWA Non-Regulatory Supplement Attachment 2 • AASHTO (2011) *A Policy on the Geometric Design of Highways and Streets* • Local jurisdiction drainage design criteria (e.g., Virginia DOT *Drainage Design Manual*)
Hydraulics	• Crown elevation • Embankment elevation • Setback and right-of-way elevations • Flood frequency–based risk of traffic interruption	• U.S. DOT "Climate Adaptation Plan 2014 Ensuring Transportation Infrastructure and System Resilience" • AASHTO (2007) *Highway Drainage Guidelines* • FHWA (2016) *HEC-17: Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience*
Drainage	• Superelevation transitions of zero cross slope away from sump/sag area of vertical curves • Cross slopes identified to ensure positive drainage toward outer edges of travel lanes • Ditch shapes, depths, lining materials, and grades designed to minimize erosion • Appropriate inlet/catch basin spacing, subbase drainage, including underdrains and cross drains; inlet and storm sewers "over designed" in areas where overland relief is not available • Drainage design accounts for partial clogging of inlets; combination analysis for throat and grate inlet configurations • Riprap sized for velocity and outlet configuration of stream bank • Stormwater detention design and placement (e.g., detention basins)	• FHWA Highway Subdrainage Design • AASHTO (2007) *Highway Drainage Guidelines* • AASHTO Model Drainage Manual • AASHTO (2011) *A Policy on the Geometric Design of Highways and Streets* • Local jurisdiction Drainage Design Criteria (e.g., Virginia DOT *Drainage Design Manual*) • Local jurisdiction roadway design manuals for establishment of superelevation placement and rate standards (e.g., Virginia DOT *Road and Bridge Standards)*
Materials	• Gradation options: impervious (dense and compacted), low permeability (gap graded, e.g., stone matrix), permeable (open graded) • High-viscosity binder preferred • Pavement additives resistant to moisture damage	• 1993 AASHTO *Guide for Design of Pavement Structures* • Local jurisdiction material design requirements (e.g., Virginia DOT Materials *Manual of Instructions* and 2014 *Secondary and Subdivision Pavement Design Guide*)

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Table 6. (Continued).

Topic	Design or Regulatory Considerations	Example Guidance
Erosion and Sediment Control	• Flow depth • Flow direction • Velocity • Discharge • Width • Presence of debris • Use of geotextiles • Landscaping and slope planting • Temporary measures during construction	• AASHTO *Guide for Transportation Landscape and Environmental Design* • Department of Environmental Quality Erosion and Sediment Control Handbook • Local jurisdiction guidelines and standards
Overtopping	• Assumes weir flow • Velocity • Head (elevation of overtopping water minus road-surface elevation) • Flood frequency at which overtopping occurs	• FHWA (2016) *HEC-17: Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience*

Some states and regions are undertaking efforts to develop design guidelines to account for non-stationarity and the associated potential impacts. For example, California is using geographic information systems to conduct a comprehensive vulnerability assessment of its transportation network. The state aims to identify "hot spots" that could be particularly vulnerable to climate change based on the National Academy of Sciences' *Sea Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future* (National Research Council, 2012), as well as two 2009 research reports by the California Energy Commission's Public Interest Energy Research program—*The Impacts of Sea Level Rise on the California Coast* (2009b) and *Climate Change Scenarios and Sea Level Rise Estimates for the California 2009 Climate Change Scenarios Assessment* (2009a). New York City is developing climate-resiliency design guidelines for publicly funded buildings and infrastructure, including transportation, based on climate projections developed by the New York City Panel on Climate Change.

Evaluating If Adaptation Is Needed When Guidelines Are Not Available

Where climate change design guidelines do not exist, agencies can ask questions such as those following and depicted in the decision tree in Figure 12 to determine whether design more resilient to extreme weather and changing climate is likely to be desirable from an economic loss-avoidance perspective. These questions consider the interactions between climate, infrastructure, land use, and population changes. Changes to timing, frequency, and magnitude of design-relevant events need to be considered as well.

- Does the historical record show changes relevant to the design of the assets under consideration (i.e., is the asset or corridor under consideration climate-sensitive; will it experience higher levels of damage when subjected to small climate variations)?
- Do climate scenarios show changes relevant to the design of the assets under consideration (i.e., is climate a dominant risk factor; at what point does an agency want or need to take action to prevent or diminish climate impacts)? Transportation agencies may need to develop their own definitions of "dominant risk factor" based on their own criteria, such as repair costs exceeding *X* percent of the inflation-adjusted original investment, an asset failing *X* years before the end of its useful life, an increase by *X* percent or number of traffic accidents, and so on.

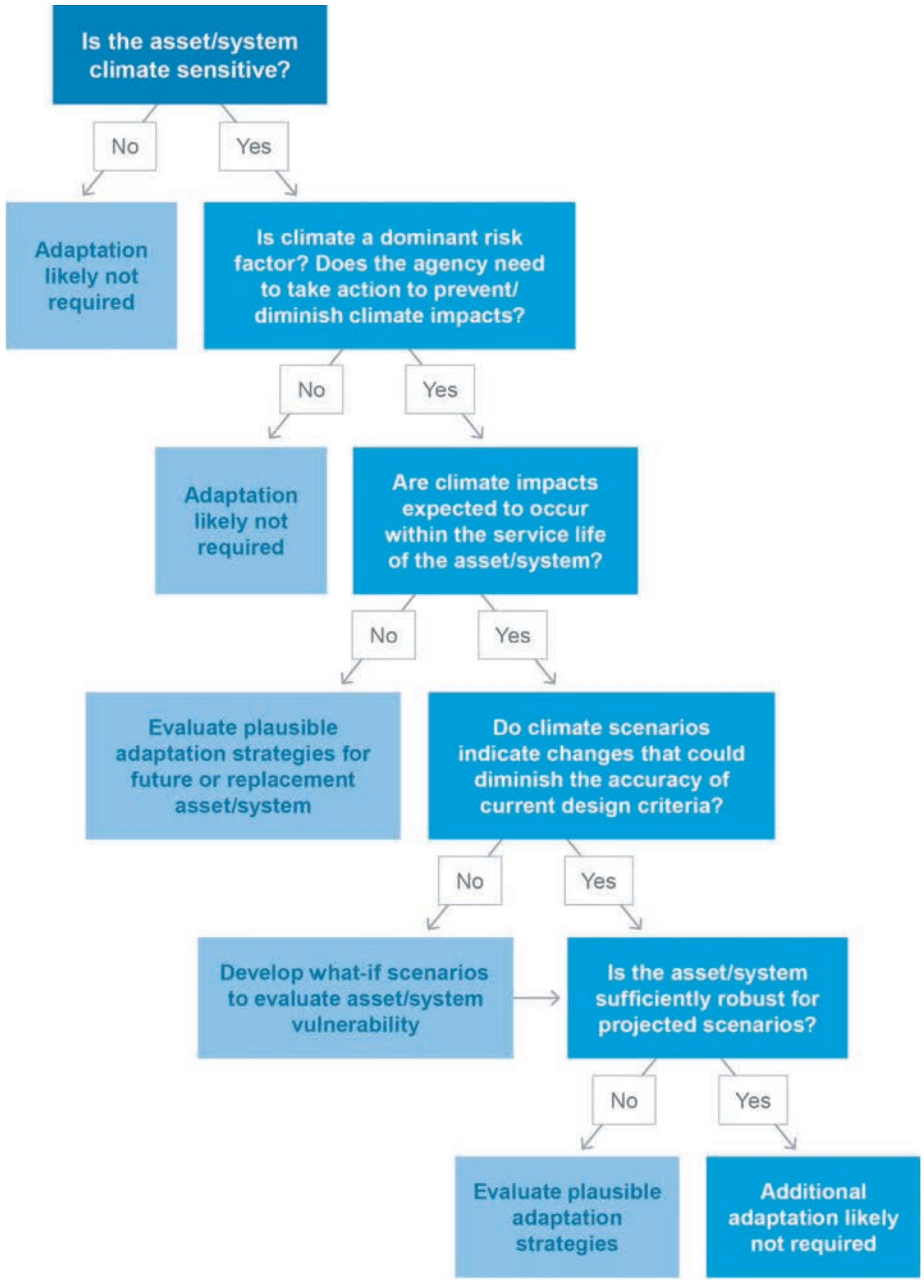

Figure 12. A decision tree can help inform decisions about whether to adapt to climate change and extreme weather.

- Do the scenarios agree, or mostly agree, on the direction of those changes (i.e., all show either an increase or a decrease)?
- If the changes are expected in the future, are they expected within the service life of the asset?
- Do either or both the historical record and climate scenarios show changes in a direction that would require more robust design (i.e., can the existing asset or system cope with the projected climate changes and is the existing system sufficiently robust?) Have or will factors such as land use changes exacerbate observed or predicted changes (e.g., to runoff)?
- Have or will factors such as population growth increase the number of users who are or will be affected by observed or predicted changes?
- Are there long-term trends, especially inundation vulnerabilities, which suggest that asset maintenance or construction in this area may not be viable (e.g., Zillow, the National Oceanic and Atmospheric Administration [NOAA], regional or state climate impact studies)?

Transportation agencies can use the listed authoritative references to work through these questions, representing the best available science and engineering guidance as of this writing. Useful FHWA references for evaluating if and how to incorporate climate change adaptation into planning, design, and O&M include

- HEC-25, volume 2 (https://www.fhwa.dot.gov/engineering/hydraulics/pubs/nhi14006/nhi14006.pdf), for assessing extreme events in the coastal environment;
- HEC-17 (https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf) for assessing extreme events in riverine environments; and
- HOP-15-026 (https://ops.fhwa.dot.gov/publications/fhwahop15026/fhwahop15026.pdf) for adapting transportation systems management, operations, and maintenance to climate change.

Incorporating Climate Change into Cost-Benefit Analysis

For assets or systems deemed critical or long-lived, as well as vulnerable to climate change scenarios selected by the DOT, a range of adaptation strategies may be developed. For planning a water resources project, for example, the final decision to incorporate adaptation measures for either gradual changes in more frequent events or changes in the magnitude of extreme events is determined by

- Funds available,
- The vulnerability and criticality of the asset or corridor affected, and
- Whether the benefits outweigh the costs for continued maintenance in certain areas (and obligations for the public disclosure of such situations) on the business-as-usual path and for each adaptation option.

Limited funds may dictate that only adaptive measures related to gradual changes or smaller but more frequent events can be implemented, while additional funding may allow the incorporation of adaptive measures related to extreme events. Either way, a transportation agency may consider whether the benefits outweigh the costs for continued maintenance in certain areas on the business-as-usual path, then communicate this to the legislature and public in the agency's funding and policy capacity. Thus, the public and their representatives have some of the data they need to consider whether the business-as-usual path is delivering what they want (Figure 13). The public can also discern if it is worthwhile and a better fit with their values to invest in another path that would prevent climate change, such as transitioning away from fossil fuels, though certain adaptations may still be desirable to manage risk unless or until the transition is accomplished.

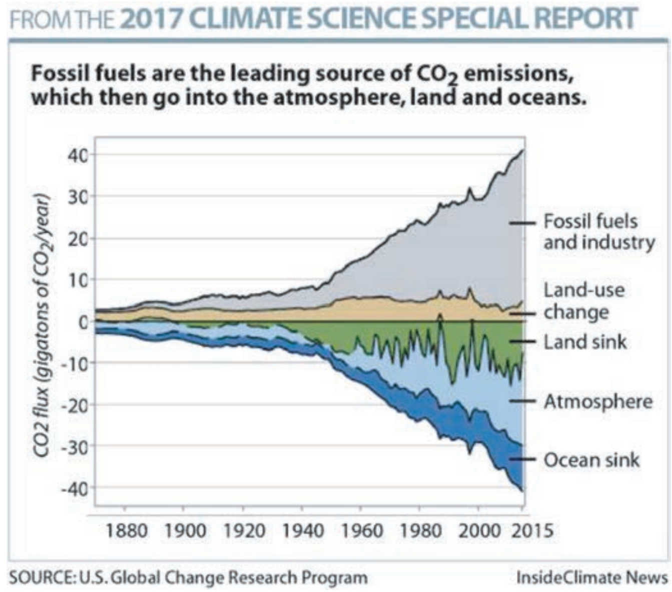

Figure 13. Decision makers need to determine if they want to remain on a business-as-usual path or want to pursue other policies (USGCRP, Figure 2.7, 2017).

Update to the Scenario

The replacement culvert will have an expected useful life of 30 to 50 years, depending on the design. The replacement is expected to be accomplished in the next 2 years at the same location as the existing culvert; therefore, designers should consider expected precipitation conditions between 2049 and 2069. Conservative assumptions would use a 50-year useful life and precipitation conditions around 2069; however, designing for climate conditions at the end of the asset's useful life could be overly conservative, and often in practice 60 percent of the design life is used. In this case, that would be 30 years, which equates to 2049. Designers should also consider current precipitation conditions; some areas of the country are predicted to become drier than they are currently. The more conservative (i.e., higher-flow) condition will be used to design a new structure.

A spreadsheet-based tool was developed to predict the changes in peak discharges (Q_p) and the risk associated with climate change. Data input to the tool include current rainfall frequency-depth-duration curves (from NOAA Atlas 14 or similar sources), the location zip code, drainage area, curve number, and time of concentration (T_c). The tool evaluates a rainfall temporal distribution for each recurrence interval (T_r). The changes in 24-hour design storms caused by climate change were obtained from EPA's SWMM-CAT (Climate Adjustment Tool). A climate change outcome of warmer, wetter conditions for the far term (2045–2074) was selected for analysis, as this is consistent with predictions for the Chesterfield, Virginia, area. Peak discharges for current and future conditions were calculated

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and adjusted to be statistically consistent with their corresponding recurrence intervals. Discharges for future conditions were found to be higher than those for current conditions, so future discharges were used in the design calculations for the new structure.

Data needed at this stage include

- Expected useful life of current facility,
- Expected useful life of replacement facility,
- Anticipated time frame for implementation of adaptation strategies,
- Scenarios to be used for analysis, and
- Recurrence interval of the design event.

Data needed for flood events include

- Flood discharge/flow rates (or other parameters of interest) for events with recurrence intervals that exceed the design event recurrence interval (i.e., if the design event recurrence interval is 50 years, you will also need data for the 100- and 500-year events).
- 24-hour precipitation data for the design event recurrence interval plus recurrence intervals that exceed the design event recurrence interval.
- Flood discharge/flow rate (in cubic feet per second or other parameter of interest) of the design event.

Optional information needed includes

- Tools or software that could be used for analysis of future hazard conditions based on the selected scenario (to ensure the selected scenario and related data are compatible with the tools and software to be used).

CHAPTER 4

Common Costs

Financial Costs

Total Project Costs

The total project cost, or life-cycle cost, is the amount of money a project costs for pre-construction planning and design; required property acquisition; construction of the project; O&M costs throughout the life of the project, including periodic repairs or replacement costs; and disposal or decommissioning costs at the end of the project's life. O&M costs can be positive, negative, or zero, depending on whether the project will increase, decrease, or have no net effect on O&M costs compared with existing costs.

FHWA's *Life-Cycle Cost Analysis Primer* (https://www.fhwa.dot.gov/asset/lcca/010621.pdf) provides detailed information about calculating life-cycle costs for a project. All life-cycle costs need to be discounted to their NPV. Therefore, activities that will occur in the future, such as O&M, should be discounted using the NPV techniques described in Chapter 2. Construction costs are typically discounted using the mid-point of construction, so if a construction project will start 1 year from now and will last 2 years, it should be discounted by 2 years, which is the 1-year start date plus half of the 2-year duration. Cost worksheets are included in Appendix D.

Common sources of data for these costs include

- **Historic cost data.** Data from similar projects that were previously completed are likely to be included in an agency's records and can often be a good source of cost information on which to base estimates for the current project under consideration. Some agencies maintain databases of project costs, which can provide useful information (for example, Utah's system has cut project design costs by 50 percent by making such information and many of the following data sources dynamically available).
- **Published unit costs.** *Engineering News-Record* and private construction-cost companies publish and maintain information about current costs for different industry sectors, asset and facility types, and geographic locations.
- **Contractor bids.** Recent bids from public projects may be published or requested from the sponsoring agency and can provide a basis for estimating project costs, particularly for projects such as culvert installations.
- **Real estate assessments.** Online property tax records as well as publicly accessible real estate websites (such as Zillow or Redfin) contain information regarding tax rates and the values of property sites.
- **Maintenance personnel.** An agency's maintenance personnel are usually a reliable source for costs and frequencies associated with O&M of transportation system assets. These personnel might also use work order databases to track the status of work order requests; these databases can also provide information about costs associated with operating and maintaining certain assets, as well as the procedures required to complete the work.

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Delays During Construction and Implementation

Construction of a transportation project might cause delays for system users, in some cases necessitating detours. The costs associated with these delays and detours will be included in the costs of the project (Equation 4 and Equation 5). The duration of service losses or delays and the number of impacted transportation facility users is typically documented based on the proposed project design and construction schedule. The cost of passenger time is based on regional average hourly wage rate data from the Bureau of Labor Statistics and U.S. DOT guidance. Additional mileage costs are based on the additional distance traveled and the federal mileage rate in effect for privately owned vehicles, which can be found on the General Services Administration's website (http://www.gsa.gov/travel/plan-book/transportation-airfare-pov-etc/privately-owned-vehicle-pov-mileage-reimbursement-rates).

Equation 4. Cost of detours during construction.

$$\begin{aligned} Cost\ of\ Detours = {} & (\$/Vehicle/Mile) \times (Number\ of\ Impacted\ Vehicles) \\ & \times (Duration\ Detour\ is\ in\ Effect) \times (Additional\ Mileage/Vehicle) \end{aligned}$$

Equation 5. Cost of delays during construction.

$$\begin{aligned} Cost\ of\ Delays = {} & (\$/passenger/hour) \times (hour\ of\ delay/day) \\ & \times (number\ of\ passengers) \times (number\ of\ days\ delays\ occur) \end{aligned}$$

Residual Value and Salvage Value (Negative Cost)

Residual value is the estimated value of project assets at the end of the period of analysis. Salvage value is the estimated value of an asset that has a market for selling it. In some cases, a project alternative might have an end-of-project value that is substantial enough relative to total project costs that components might be worth salvaging and selling or reusing. For example, buses or train cars that are no longer needed but are still operational might be sold. The net residual or salvage value of such projects or assets is be included in the CBA as a negative cost. The residual or salvage value will have the greatest impact on a CBA if the life spans of alternatives are significantly different or if physical components of the alternatives being considered are much different (http://bca.transportationeconomics.org/costs/end-of-project-costs.).

The residual or salvage value is calculated by estimating the remaining useful life of the asset or component beyond the analysis period and determining its percentage relative to the total life of the asset (Equation 6). The percentage of life remaining is multiplied by the initial capital cost of the asset or component, converted to a present value, and subtracted from the initial capital cost (thus it is a negative cost) (MnDOT, 2017).

Equation 6. Salvage value calculation for assets with remaining useful life.

$$Salvage\ Value = \frac{Remaining\ Useful\ Life}{Total\ Useful\ Life} \times Capital\ Cost$$

Climate change may erode the underlying land value and ability to maintain the transportation infrastructure in a given locale as sea levels rise or the frequency of nuisance flooding increases. These costs are of a higher magnitude, as the base for construction may no longer exist. Again, many further expenses and investments are structured around the transportation investment (initial road or rail line, etc.) The public and legislature need to be kept informed of long-term risks to and erosion of public assets so they may make timely alternate choices, if desired.

Environmental and Social Costs

Construction of a transportation project could have short- and long-term environmental and social impacts. Potential short-term impacts associated with the act of constructing the project would generally be included with construction costs. For example, a project that requires air quality monitoring is likely to include the monitoring costs in the construction costs; however, some other impacts could be long term, for example, the loss of a wetland or habitat, loss of trees, or increased ambient noise from traffic or operations.

Determining some of these values can be challenging. Typically, environmental costs are determined by an environmental economist, as these costs can vary widely by type of impact and geographic location. If a project is expected to increase noise in the project area and a noise wall is constructed to help abate the increase, the cost of the noise wall will be included in the overall project cost. Significant increases in noise themselves are considered a detriment, and will be incorporated as a negative benefit (see Chapter 5).

Update to the Scenario

Based on the future flows estimated to account for the impacts of climate change from the selected planning scenarios, the Virginia DOT determined to evaluate three possible adaptation strategies:

- Enlarge the existing culvert,
- Add multiple culverts, or
- Replace the existing culvert with a box or arch culvert with additional capacity.

The new culverts would be designed for the future 50-year event (presently they are designed for the current 50-year event). The DOT developed cost estimates to design, construct, and maintain each of the three options under consideration based on bids received from similar recent projects as well as from cost-estimating software (Appendix E). The costs for each alternative are summarized in Table 7.

Table 7. Example scenario summary of costs of design alternatives using 7 percent discount rate.

Existing Culvert Base Construction Cost	$ 400,000			
Additional Cost to Address Climate Change	$ 150,000			
Discount Rate (%)	*7.00%*			
Present Value Coefficient (PVC)	13.80			
COSTS	**PROJECT TYPE**			
Cost Data Input	**Enlarge Existing Culvert**	**Add Multiple Culverts**	**Install Box/Arch Culvert**	**Replace-in-Kind**
Pre-construction cost (design, permitting, land acquisition, etc.)	$ *42,000*	$ *50,000*	$ *60,000*	$ 40,000
Base construction cost	$ *420,000*	$ *500,000*	$ *600,000*	$ 400,000
Ancillary costs (OH&P, contingency, escalation)	$ *105,000*	$ *125,000*	$ *150,000*	$ *100,000*
Cost of delays during construction	$ *63,000*	$ *83,500*	$ *100,200*	$ *66,800*
Salvage value	$ -	$ -	$ -	$ -
Subtotal - Project Costs	$ 630,000	$ 758,500	$ 910,200	$ 606,800
Annual O&M costs	$ *6,300*	$ *7,585*	$ *9,102*	$ *6,068*
Project useful life (years)	*50*	*50*	*50*	*50*
Subtotal - O&M Costs	$ 86,945	$ 104,679	$ 125,614	$ 83,743
Roundoff Adjustment (1,000)	$ *717*	$ *863*	$ *1,036*	$ *691*
TOTAL PROJECT COSTS (BCA - Roundoff)	**$ 717,000**	**$ 863,000**	**$ 1,036,000**	**$ 691,000**

OH&P = Overhead and profit.

For this particular project, the Virginia DOT determined that the social and environmental costs would be negligible; no critical habitats will be adversely impacted, nor will any permanent noise or air quality issues arise.

Costs were also evaluated using a 3 percent discount rate, as shown in Table 8.

Table 8. Project costs for adaptation alternatives for example culvert replacement scenario using 3 percent discount rate.

Existing Culvert Base Construction Cost	$ 400,000			
Discount Rate (%)	*3.00%*			
Present Value Coefficient (PVC)	25.73			
COSTS	**PROJECT TYPE**			
Cost Data Input	**Enlarge Existing Culvert**	**Add Multiple Culverts**	**Install Box/Arch Culvert**	**Replace-in-Kind**
Pre-construction cost (design, permitting, land acquisition, etc.)	*$ 42,000*	*$ 50,000*	*$ 60,000*	$ 40,000
Base construction cost	*$ 420,000*	*$ 500,000*	*$ 600,000*	$ 400,000
Ancillary costs (OH&P, contingency, escalation)	*$ 105,000*	*$ 125,000*	*$ 150,000*	*$ 100,000*
Cost of delays during construction	*$ 63,000*	*$ 83,500*	*$ 100,200*	*$ 66,800*
Salvage value	*$ -*	*$ -*	*$ -*	*$ -*
Subtotal - Project Costs	$ 630,000	$ 758,500	$ 910,200	$ 606,800
Annual O&M costs	*$ 6,300*	*$ 7,585*	*$ 9,102*	*$ 6,068*
Project useful life (years)	*50*	*50*	50	*50*
Subtotal - O&M Costs	$ 162,098	$ 195,160	$ 234,192	$ 156,128
Roundoff Adjustment (1,000)	*$ 792*	*$ 954*	*$ 1,144*	*$ 763*
TOTAL PROJECT COSTS (BCA - Roundoff)	**$ 792,000**	**$ 954,000**	**$ 1,144,000**	**$ 763,000**

Data needed at this stage include

- Design concepts of adaptation strategies,
- Cost estimates for each adaptation strategy (life-cycle costs, including any long-term adverse impacts from the adaptation strategy), and
- Identification of any non-quantifiable costs associated with the project.

CHAPTER 5

Common Benefits

Losses Avoided

For hazard mitigation and resilience projects, benefits are typically avoided damages and losses, as shown in Equation 7.

Equation 7. Determining project benefits.

$$BENEFITS = \Sigma(Pre - PROJECT\ EVENT\ DAMAGES\ AND\ LOSSES) \\ - \Sigma(Post - PROJECT\ EVENT\ DAMAGES\ AND\ LOSSES)$$

Avoided damages and losses are physical damage and service losses that would occur as the result of a hazard or incident if the project were not undertaken. For example, if a 100-year flood event will cause $1 million in damages, a resilience project that will protect against the 100-year flood event with no residual damages has avoided losses valued at $1 million, which is considered a project benefit.

Project benefits occur over a future period of time, while most project costs are incurred up front and in the present. For this reason, benefits are more difficult to estimate than costs. Furthermore, many benefits that come with avoidance are difficult to quantify. Zillow's analysis provides one indication of costs of the current (business-as-usual) path and thus some indication of the savings that may be achieved by avoiding it. Yet, Zillow analyses apply only to residential property, not to the residential streets, arterials, local and state highways, and interstates connecting them, or to the other public resources such as schools, parks, libraries, government buildings, and more (not to mention the private sector businesses providing much of an area's employment).

The National Climate Assessment (USGCRP, 2014) also points out that we are currently pursuing a path whereby the consequences of climate change could be beyond adaptation: 18°F Arctic warming, sea levels rising 1 foot per decade, and widespread drying—or Dust-Bowlification as Joe Romm (2017) called it in *Scientific American* and the scientific journal *Nature*—along with 8°F to 10°F warming over the interior of this country (Figure 14) (NASA, 2015). These are averages; the temperature extremes that occur annually are higher already and would be much higher in the future, continuing on our current path. In that case, global sea levels may rise 8 feet, inundating every major coastal city in the United States and around the world by century's end. (The Intergovernmental Panel on Climate Change estimated 2 meters of sea level rise [SLR] could occur this century on the current path. NASA scientists and others have said that over 3 meters of SLR by 2100 is possible.) Seas would keep rising by more than 1 foot a decade thereafter, making adaptation all but impossible.

The unaffordability and impossibility of adapting to the degree of climate, food system, security, and economic change in store makes a rapid shift to new technologies our best, lowest-risk,

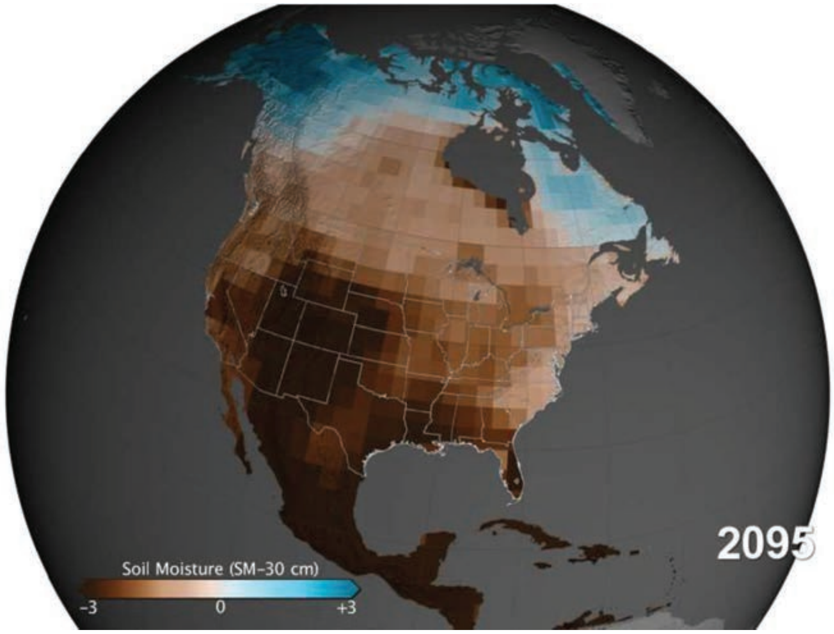


Figure 14. Gradual warming of the atmosphere over the interior of the United States will decrease soil moisture (NASA, 2015).

most cost-effective bet. However, because these technologies are new and not completely proved, quantifying the benefits from their implementation could be challenging. Further, some technologies still in development could become available at some point in the future; these technologies cannot be accounted for in CBAs performed today. CBAs can be completed based on the best available information at the time then re-calculated in the future based on newly available information as appropriate.

Most climate adaptations are incorporated with the objective of reducing damage from future natural hazard events; however, some projects might also seek to improve existing conditions under normal operations, and as such the project has direct benefits. Both losses avoided and direct benefits are considered to be benefits in a CBA; however, care needs to be taken not to double-count benefits. Double-counting occurs most frequently with transfer payments and counting the same economic impact twice. An example of double-counting a transfer payment is when a toll is reduced and the analysis also includes lower vehicle-operating costs, even though the cost of collecting the toll remains unchanged (bca.transportationeconomics.org). The toll is a transfer payment between the transportation agency and the user and therefore is not included in a CBA. An example of counting the same economic impact twice is the construction of a noise barrier. If the cost of constructing the barrier is included in the project costs, the disbenefit (or negative benefit) of noise from the project without the wall would not be included in the CBA.

Damage Reduction

Damages from a natural hazard event (such as a flood) can include physical damages to facilities as well as related costs. Avoiding or reducing these damages by implementing adaptation measures to accommodate future expected conditions is considered a benefit in a CBA. Benefits that can be realized by avoiding damages are grouped into the following five categories. (One category, transportation service losses, can be a significant source of damages/losses for transportation agencies, and is therefore described in greater detail.)

- **Physical damages** include the cost of permanent repair or replacement of fixed facilities (roads, bridges, structures) and associated equipment (movable signs, agency vehicles, equipment, and contents of structures). Physical damages can occur to buildings that support transportation operations; building contents; infrastructure, including utility and transportation elements; vehicles; equipment; and site features such as landscaping, environmental contamination, or erosion. Physical damages are often the largest component of the total damages resulting from a natural hazard event. Physical damages to transportation assets could include damages to roads, bridges, and tunnels; support structures such as culverts, embankments, guardrails, and signs; and support facilities such as administrative offices, toll plazas, and weigh stations.
- **Response and recovery costs** include initial emergency protective measures and other temporary facilities established in response to natural hazard events to facilitate recovery of basic transportation service. Some examples of response and recovery costs include sandbagging to protect entrances and openings to facilities, deploying flood barriers and flood gates, and pumping floodwater out of facilities. Transportation agencies might also temporarily close vulnerable parts of the system such as roads susceptible to flooding or bridges affected by high winds, and put up temporary signs to guide network users through detours and evacuation routes. Such costs may include DOT or agency force account labor, invoiced contractor labor, or volunteer labor estimated based on local average hourly wages. The costs may also include the materials used, such as sandbags and sand.
- **Other damage costs** are miscellaneous costs associated with natural hazard events, including lost revenue, debris removal, and cleanup costs needed to restore transportation service to pre-event conditions. Loss of revenue could occur for toll roads, tunnels, and bridges; bus routes; ferry service; and train or subway fares if these systems are rendered temporarily inoperable as a result of the hazard event. Records will likely indicate how long the system component was out of service, the fare structure, and average daily traffic (ADT) for the time the system was inoperable.
- **Losses to the local economy** can occur as a result of a loss of the transportation systems serving the impacted communities. Losses occur when consumer spending decreases as a result of the hazard event affecting accessibility to primary industries served by the transportation network. Examples include decreased levels of tourism and decreased attendance at sporting events, theater performances, arts events, and restaurants. When considering if losses to the local economy will be included in a CBA for grant applications, applicants need to review the requirements of the particular grant program; not all grant programs allow economic losses outside of the transportation network itself to be included in the analysis. However, economic losses can be significant if a particular segment of the transportation network is rendered inoperable for a period of time, which can be considered when analyzing project alternatives.
- **Transportation service losses** are the economic losses and additional mileage costs associated with the loss or delay of damaged transportation systems as well as with the secondary impacts on alternate transportation services, such as increased time and traffic caused by detours around a disaster-damaged road or bridge. These losses may be particularly considered for freight, as the impacts of events such as extreme heat can result in vehicle weight restrictions for certain roadways. These losses are discussed further in the following section.

Transportation Service Losses

Transportation service losses have a variety of impacts that can be avoided or reduced by the implementation of climate-adapted projects. For example, the loss of a key road or bridge could require the use of additional temporary bus or mass transit services that increase traffic and travel times while repairs are made. However, a climate adaptation could lessen or eliminate damage to the road or bridge, which would in turn reduce the use of additional bus or mass transit services, since the required repairs could presumably be made more quickly or might not be required at all.

Common service losses that can be included for consideration of losses avoided in a CBA include

- **Cost of road or bridge service.** The unit cost of road or bridge service can be based on a standard value reflecting the value of people's time. U.S. DOT published values of national averages in its annual BUILD guidance and continues to do so in relation to its discretionary grant programs (US DOT 2020). Regional values can be determined using Bureau of Labor Statistics values for average hourly wages; the FEMA Benefit-Cost Analysis Toolkit (Version 5.3.0) and the FTA Hazard Mitigation Cost-Effectiveness Tool (Version 2.2) use standard national average values that can be adjusted to reflect regional cost differences where appropriate. Standard values are based on national average values reflecting loss of regional economic impacts; therefore, no adjustments to the number of trips are required to account for residential versus commercial or emergency vehicles.
- **Delay or extra travel time.** The delay or extra travel time associated with road or bridge damage is usually recorded as hours of delay per trip and can be documented by the responsible agency or by using maps with detour travel times and associated mileages from online sources. When no alternative route or detour is available, the extra travel time can be set to a maximum of 12 hours per one-way trip and supported by a map showing no detour is available.
- **Number of affected vehicles.** The number of affected vehicles for roads is generally based on ADT counts prepared by the state or local DOT. The number of affected vehicles for bridges can be based on ADT counts prepared by the state or local DOT or by ADT data collected by the transportation agency that owns or operates the bridge. For grant applications, whenever possible, the ADT counts will be provided by the responsible agency or included in a signed letter from a local official. For smaller subdivision roads or crossings where traffic counts are unavailable, users can estimate one-way trips using the TRB *Highway Capacity Manual* (2016) or other recognized sources.
- **Loss of function durations.** The duration of service losses or reductions is based on the number of hours, days, or weeks that the transportation asset is out of service. The service losses associated with each historic event can be obtained from state or local DOT records, other agency records, disaster damage worksheets (i.e., FHWA Damage Assessment Forms or FEMA Project Worksheets), or news articles citing credible sources where the date of the article can be linked to the date of the event.
- **Additional mileage.** The additional mileage associated with traveling around a flood-damaged road or bridge can be documented by the responsible agency or by using copies of maps with detour travel times and associated mileages from online sources. This additional mileage can then be multiplied by the number of affected vehicles and the standard mileage rate for privately owned vehicles, which can be found on the General Services Administration website (https://www.gsa.gov/travel/plan-book/transportation-airfare-rates-pov-rates-etc/privately-owned-vehicle-pov-mileage-reimbursement-rates). Once the additional mileage data are collected, the additional loss of service for each event can be determined based on the formula in Equation 8.

Equation 8. Calculating loss of transportation service to be included in a CBA.

$$\begin{aligned}\text{Additional Loss of Service} &= (\$/\text{Vehicle}/\text{Mile}) \times (\text{Number of Affected Vehicles}) \\ &\quad \times (\text{Loss of Function Duration}) \times (\text{Additional Mileage}/\text{Vehicle})\end{aligned}$$

Sources of Data

Sources of data for determining these benefits can include historic information as well as predicted costs based on planning and engineering studies. Some common data sources include

- **Historic records.** Agencies can use data from previous incidents to develop estimates of physical damages, response and recovery costs, and other damages.
  - **Disaster damage worksheets.** Disaster damage worksheets such as FHWA Damage Assessment Forms or FEMA Project Worksheets are useful for documenting historic damages to transportation facilities from presidentially declared disaster events. Such damage worksheets may include permanent repair and restoration of physical damages as well as response and recovery costs.
  - **Repair records.** Repair records from a state or local DOT or Department of Public Works may be useful for documenting historic damages to various transportation facilities from flood events. Such repair records may include records of expenditures in financial databases, receipts for repairs or equipment rental, or force account labor records, and may be supported by other documentation such as news articles or community and agency board meeting minutes. Complete copies of records need to be included in grant applications, with costs organized in a spreadsheet.
  - **Flood insurance claims.** Insurance claim data may be useful for documenting physical damages to insured properties from various flood events. Flood insurance claim data on all properties insured under the National Flood Insurance Program are available through BureauNet (https://nfipservices.floodsmart.gov/home/reports). Transportation agencies can register to obtain information on the various properties insured under the National Flood Insurance Program within their community. Additional benefits may be estimated from flood claims data when other event information is available. For example, if the flood claim lists only building damages, but the building type and size and the depth of flooding in the building are known, then FEMA depth-damage functions can be used to extrapolate contents damages and even displacement costs for that event.
  - **News articles citing credible sources.** News articles can include nationally or locally published newspapers or newsletters that are printed or posted online. Articles are most useful if they indicate the specific dates and impacts to facilities to be addressed by the proposed project.
- **Engineering reports.** These reports can indicate estimated damages to various types of transportation facilities based on similar historic events or detailed engineering analysis.
- **Transportation agency studies.** Agency studies provide another good source of estimated damages to transportation facilities.
- **Software estimates.** For transportation structures such as administration buildings and storage facilities, expected flood damages can be estimated using software such as the BCA software or HAZUS-MH, both offered by FEMA:
  - Flood damages to buildings can be estimated using depth-damage functions based on structure information (building type, number of stories, foundation type, size and building replacement value) as a function of flood depth above the first-floor elevation. It is important to establish the correct reference point for the first-floor elevation before applying the depth-damage functions.
  - Depth-damage functions can be documented from the FEMA BCA software or the HAZUS-MH output, or transcribed into a separate document or spreadsheet.
  - Structure information can be documented from various sources, including tax records, structure plans with dimensions, site photographs, engineering reports, and building cost data.

Other software such as the U.S. Army Corps of Engineers' HEC-FIA and HEC-WAT may also be used to estimate damages to buildings from flooding.

Once these historic flood damages are determined, the total damage cost for each event can be determined based on the formula in Equation 9:

Equation 9. Calculating total damages.

$$Total\ Damage = (Physical\ Damage) + (Response\ and\ Recovery) + (Other\ Damage)$$

System Costs

DOTs have less experience including systemwide costs and other more indirect costs, but estimates of these costs are sometimes available from insurance partners and past disasters. For example, business closure and continuity costs, business loss costs, job loss costs, and cumulative individual and community impacts may all stem from lack of transportation system access or availability. These costs are substantial. They are tied to the DOT's core mission and may affect more than one mode of transportation. In some cases, the magnitude of system costs can tip the balance toward the importance or necessity of avoiding disruption, and this is when adaptation planning projects present the clear economic benefits of avoiding climate change in the first place. System costs can even be deemed a necessity when considering unpayable costs. For this reason, transportation system costs typically involve different decisions than the ones used to determine the size of infrastructure. Rational and comprehensive planning will extend to these real-life, systemwide impacts, and consider how they can or should be avoided and how the agency or jurisdiction can contribute.

Additional flood-related costs beyond increased heavy storms (see Figure 15) or sea level rise come from increasing "sunny day" or "nuisance" flooding from tides, which are also higher with rising seas (USGCRP, 2014). What are the tipping points for cities or other areas? NASA (2015) and Sweet et al. (2017) looked at property and city areas subject to repeat inundation 26 times per year or more, making some parts of the city inaccessible (e.g., areas that could be abandoned earlier). What are the thresholds for habitation? When cars and trucks can no longer be insured? Currently, 60,000 miles (96,561 kilometers) of roadways are exposed to coastal storms (Douglass et al., 2014). In the future, rising seas will cause more severe events and more frequent disruptions and damage, and storm-surge impacts will extend further inland. For example, the

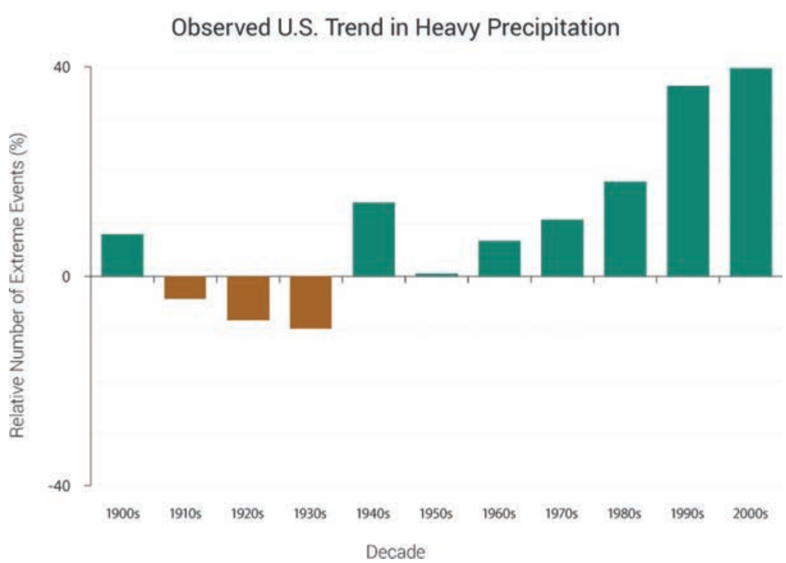


Figure 15. An increasing number of heavy precipitation events will increase flood-related costs for transportation agencies (USGCRP, 2014).

storm-surge extent from Hurricane Sandy in 2012 matches or is exceeded by the chronic (twice a month) inundation by 2100 (Dahl, 2017). Over the past 20 years, the frequency of nuisance floods has nearly doubled and is projected to continue to increase at all locations; the total induced vehicle hours of delay caused by nuisance flooding currently exceeds 100 million hours annually and could exceed 1 billion vehicle hours by 2060 (Jacobs et al., 2018). In fact, Schrank et al. (2015) estimated that in 2014, total travel delay for the United States was 6.9 billion hours. Vehicle hours of delay from nuisance flooding on the East Coast alone will exceed that level by 2100 for the intermediate scenario, and by 2060 for the extreme scenario in Jacobs et al. (2018).

On November 5, 2017, many cities marked where the highest king/astronomical tide of the year reached; that is where they can expect the water to be most days by 2050, meaning, for example inundating low-lying areas throughout Charleston, South Carolina, and Hampton Roads, Virginia, with water peaking at 2 feet above mean sea level. Scientists have now documented a record number of "nuisance flooding" events during high tides. During high tides in 2014, nearly half of residents in Hampton Roads, Virginia, could not get out of their neighborhoods at least once because of tidal flooding (Virginia Institute of Marine Science, 2017).

Environmental Benefits

Most often, environmental benefits incorporated into a transportation CBA are "losses avoided" from a reduction in emissions to the atmosphere (i.e., improved air quality). In addition to the financial benefits that can be realized from avoided losses, some transportation climate adaptation projects also provide environmental/ecosystem services that add, expand, or improve beneficial goods and services provided by nature for people and the environment. Such beneficial environmental/ecosystem services include providing food, air quality, water quality, wildlife habitat, regulation of natural processes (i.e., flood, drought, and wildfire control), climate, and open space for recreation or other beneficial uses. For example, a bioswale or rain garden can delay and decrease the flow of stormwater runoff, reducing nuisance flooding across a key road while improving water quality, air quality, and aesthetics (Figure 16). Trees planted to help control stormwater runoff could also help improve air quality, which might be considered a *co-benefit*. Co-benefits are additional benefits that result from an implemented action or policy above and beyond the primary intended benefit. Some other common co-benefits of climate adaptation measures include improved health and wellness, improved water quality, and reduced erosion.

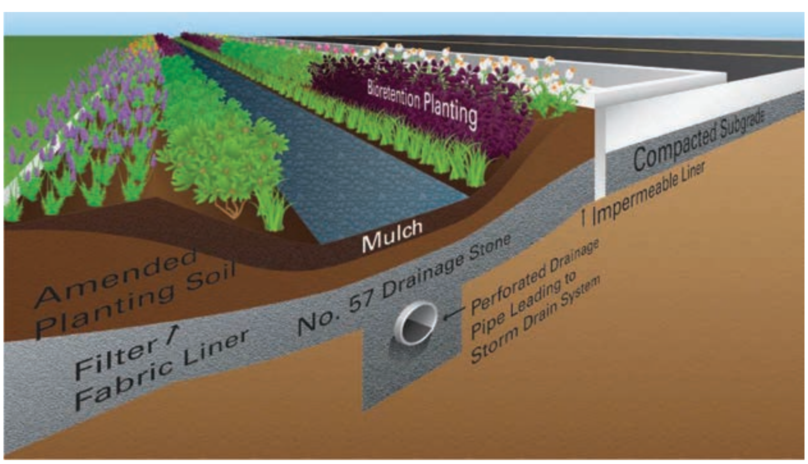


Figure 16. Green infrastructure techniques such as bioswales can reduce the velocity and volume of stormwater runoff while also capturing and biologically degrading pollutants carried by stormwater runoff (figure courtesy of Dewberry).

Greenhouse Gas Emissions

As discussed in Chapter 3, GHGs are one of the major contributors to climate change. These gases are composed primarily of CO_2, which accounts for over 80 percent of all GHGs in the United States, but also include methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (from air conditioning, refrigeration, and industrial processes). In fact, the CO_2 concentration has risen about 40 percent to 403 parts per million (ppm) over the past 150 years, with an average growth of 2 ppm per year in the last 10 years (and 3 ppm over the last year) (World Meteorological Organization, 2017). Unfortunately, the residence time of GHGs in the atmosphere is expressed in terms of centuries rather than years or even decades, as shown in Figure 17.

According to the EPA's *U.S. Greenhouse Gas Inventory Report: 1990–2014* (https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014) (U.S. EPA, 2016c), the transportation sector accounts for approximately 26 percent of GHGs in the United States as the result of burning fossil fuels such as gasoline and diesel in vehicles. The EPA's Motor Vehicle Emission Simulator (MOVES) program (https://www.epa.gov/moves) can be used to estimate emissions for mobile sources at the national, county, and project levels. California also has models that can estimate emissions, such as the EMFAC model and the California Air Resources Board's Greenhouse Gas Inventory.

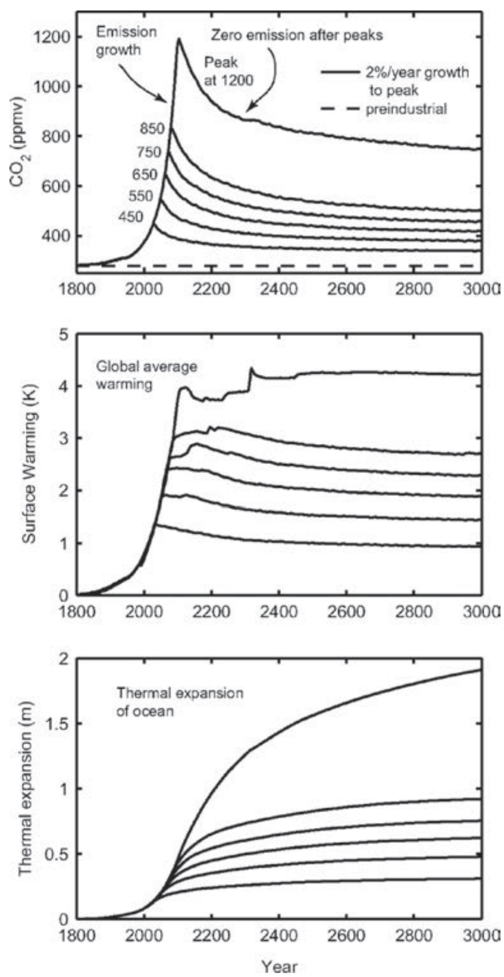


Figure 17. Greenhouse gases remain in the atmosphere for centuries after they are emitted (Solomon et al., 2009).

Many attempts have been made to monetize the value of GHGs so that their impacts to the economy can be calculated and incorporated into economic models. The social cost of carbon is the monetized value of damages caused by a 1 ton increase in GHG emissions in a given year (Brookings Institution, 2017). Current monetized estimates used in the United States come from the Interagency Working Group (IWG) on the social cost of carbon (SC-CO_2). They produce four estimates:

- Cost per metric ton avoided for a 5 percent discount rate and the average of SC-CO_2 model estimates
- Cost per metric ton avoided for a 3 percent discount rate and the average of SC-CO_2 model estimates
- Cost per metric ton avoided for a 2.5 percent discount rate and the average of SC-CO_2 model estimates
- Cost per metric ton avoided for a 3 percent discount rate and the 95th percentile of the frequency distribution of SC-CO_2 model estimates.

The IWG states that ranges of 7 to 23 percent should be used to adjust the global values to domestic values. The values per metric ton of CO_2 current as of this writing are available on the EPA's Social Cost of Carbon technical support document (2010b).

From a cost-benefit perspective, a key element in the analysis is the consideration of trade-offs between a business-as-usual approach and an adaptive approach to addressing GHG-reduction concerns. Many DOTs are charged with GHG-mitigation efforts, such that sometimes reductions in GHGs are incorporated into capital-improvement projects as a benefit, often qualitatively, as the losses or benefits produced by GHGs affecting the atmosphere cannot be reliably quantified in dollars for a CBA estimate. Nonetheless, when transportation agencies are endeavoring to make a choice between two options with similar CBAs, they may find it useful to also consider whether one option better meets the agency's GHG-mitigation goals and qualitatively "weight" that option. For example, a DOT is considering two adaptation projects, one that has little impact on GHGs and the other that reduces GHGs in accordance with the agency's long-term goals. The project having little impact on GHGs has a BCR of 1.05, while the project that reduces GHGs has a BCR of 1.01. Both projects are considered cost-effective, with the project that does not reduce GHGs being slightly more cost-effective than the project that does reduce GHGs. Because the DOT has GHG-reduction goals and the project is cost-effective, the agency might qualitatively state the project that reduces GHGs also helps to meet other program goals, and hence is considered the better option. In essence, with close CBA estimates, the potential for GHG reduction (or comparatively lower emissions) could be used as a tiebreaker for agencies that also have GHG-mitigation missions.

Other Emissions/Air Pollution

In addition to GHGs, transportation system assets can release other gases that are harmful to the atmosphere and human health. Chief among these are nitrogen oxides (NO_x), which form when fuel is burned at high temperatures. NO_x play a major role in mixing with other volatile organic compounds in the air to form smog on hot summer days (U.S. EPA Region 1, 2019). The IWG also developed a monetized estimate for the value of NO_x reductions in the United States. The estimate range varies by a factor of 10 (Interagency Working Group, 2016). FHWA's *Benefit-Cost Analysis Guidance for Discretionary Grant Programs* provides recommended values to use in CBAs for NO_x and other emissions (available from https://www.transportation.gov/office-policy/transportation-policy/benefit-cost-analysis-guidance).

Air pollution is now the world's largest single environmental health risk, and combustion motor vehicles are a contributor. The science is significantly more established than that on climate change, according to Dr. George Thurston, co-author of the World Health Organization's Global

Burden of Disease air pollution report (GBD 2015 Chronic Respiratory Disease Collaborators, 2017), who says, "The relationship between ambient air pollution exposure and human mortality is even more definitively quantified, with a broad scientific consensus, than the relationship between human activity and climate change, likely because death is a more definitively defined endpoint than climate change" (Howard, 2017).

Many of our key transportation challenges are interrelated. Air pollution has driven many of the fastest movers (London, Paris, China) to accelerate the phaseout of fossil fueled vehicles. Further, health and well-being is one of Americans' highest areas of concern and interest across the political spectrum, and health and well-being turns out to be more affected by traffic and air pollution than previously realized. Doctors and researchers are quantifying much more extensive mental and physical implications than the "old set" typically cited (i.e., asthma, emergency room visits, lung cancer, stroke, and early death). In Los Angeles, for example, more than 5,000 people die prematurely from air pollution every year, more than from traffic accidents and crime combined (SCAQMD and CARB, 2011).

The "right to public health" and life free of these pollutants are emerging themes among the public, doctors, and health advocates that will increasingly affect transportation agencies. Already agency executives in multiple countries have made announcements to this effect. A recent report by the American Lung Association estimates the costs of climate and air pollution from passenger vehicles in California to be $15 billion annually (Holmes-Gen and Barrett, 2016).

Noise

As was briefly discussed in Chapter 4, noise can be annoying and even harmful to humans by impairing hearing, increasing stress, and disturbing sleep. Projects that significantly reduce ambient noise from transportation operations are considered beneficial and can be included in a CBA. Conversely, significant increases in ambient noise from transportation operations are considered a disbenefit in a CBA. It can be difficult to assign a monetary value to noise impacts. As previously discussed, noise abatement measures are typically included as a project cost. In some cases, though, significant noise differences can affect surrounding property values such that the difference can be included in the CBA as a benefit (or a negative benefit, depending on the circumstance).

Incorporating Environmental Benefits into Cost-Benefit Analysis

Based on the data from the IWG, U.S. DOT publishes values of emissions with their discretionary grant application materials. Values for volatile organic compounds, NO_x, particulate matter, and sulfur dioxides (SO_x) are fixed. GHG values vary with time and discount rate; TIGER provided tables for the 3 percent discount rate, but FY 2018 guidance does not include a recommended value because the guidance documents on which the TIGER tables were based have been rescinded. The FY 2018 guidance indicates that any such discounts should be at the same rates as costs and other benefits quantified in the CBA and should be based on the domestic damages of such emissions, rather than on global values.

Social Benefits

Not all adaptation measures will be developed and designed solely for the purpose of avoiding future damages and losses. Some might also be designed to provide a specific benefit. While these measures might not be incorporated solely for climate adaptation, their benefits can be included in a CBA.

Increase in Active Transportation

Implementation of active transportation modes such as bicycle lanes provides social benefits in terms of health and livability, in addition to environmental benefits associated with decreased GHGs. A bicycle lane designed and constructed to decrease traffic congestion can lead to fewer vehicles on the road, which results in lower vehicle-operating costs for people who choose to use the bicycle lane rather than drive, also resulting in permanent decreases in GHGs and other emissions. Individuals who use the bicycle lanes might also experience health benefits associated with exercise. See Table 16-123, "Summary of Findings on Direct Relationships Between the Non-Motorized Travel Environment and Measures of Adult Exercise and Health" in *TCRP Report 95: Traveler Response to Transportation System Changes Chapter 16—Pedestrian and Bicycle Facilities* (http://www.trb.org/Publications/Blurbs/167122.aspx).

Environmental Justice

Low-income and minority neighborhoods and communities may be more significantly affected by climate change and extreme weather events than the general population because they have fewer resources available to cope with these impacts. For example, some low-income households do not have private automobiles and must rely on public transportation. During natural hazard emergencies such as hurricanes and floods, their ability to evacuate depends on the availability of public transportation. During heat waves, public transportation users may need to wait outside in the extreme temperatures, which could adversely affect their health as a result of heat-related illnesses or poor air quality. Low-income neighborhoods are often located in areas with lower property values associated with greater risk, such as in floodplains (Lee and Jung, 2014).

Climate adaptation strategies for transportation systems can contribute positively or negatively to environmental justice. Care needs to be taken to minimize adverse impacts, such as designing transportation improvements to direct surface water runoff away from communities in low-lying areas. Including these susceptible populations in the planning process can result in positive impacts such as the development of more walkable communities, which could decrease adverse health impacts associated with exposure to poor air quality and actually improve health impacts from exercise. Expanding low-cost transportation options could also provide greater mobility for low-income households. Green infrastructure projects such as bioswales or tree planting can not only decrease flooding but also improve water quality, improve aesthetics, and provide shade on hot days. FHWA and EPA have several publications available to help transportation agencies minimize adverse impacts from climate change on communities while providing transportation benefits.

Stress and Anxiety

Disasters that cause loss of transportation function can increase stress and anxiety on system users as they are forced to find alternative means of getting to and from various locations such as work. This added stress can result in lost productivity. In some cases, the anxiety induced by a disaster can require people to seek mental health treatment. Several agencies, such as FEMA, allow the mental stress prevented by an adaptation project to be included in a CBA. FEMA's *Final Sustainability Benefits Methodology Report* (2012) provides additional information about estimating the values of avoided mental stress.

Much is not covered in climate change cost and impact estimates. Climatewise, a voluntary group made up of 28 of the some of the world's biggest insurance companies, has warned extreme weather disasters have put this year on track to be one of the most expensive on record, urging the insurance industry to redouble efforts to tackle the huge shortfall in global coverage. Climatewise has found that extreme weather disasters over the past decade have contributed to a global climate risk protection gap of $1.7 trillion, the majority of which has been borne by governments and civil society (Holder, 2017). In a recent update, Climatewise has detailed how a growing "climate risk protection gap" has been exposed by 2017 events such as Hurricane Harvey in Texas, which alone cost the United States $180 billion in losses. This does not begin to assess mental stress resulting from losses of (or difficult interruptions in) transportation, work and employment, and housing and other familial disruptions.

Aesthetics and Other Difficult-to-Quantify Benefits

Some transportation improvements, particularly vegetative improvements intended to help lessen the impacts of heavy precipitation and flood, are also aesthetically pleasing to transportation system users and the local community. The aesthetic value, while real, is difficult to quantify, as each individual places a different value on it. Often, aesthetic benefits and other difficult-to-quantify benefits are included in a CBA as qualitative benefits and such improvements to public space are increasingly acknowledged and valued. A written description of the measure and the benefit it provides is included with the quantitative CBA so that all benefits offered by a particular approach are captured and compared with the evaluation criteria during the project selection process.

Safety

Safety is of paramount importance to transportation systems; as part of the FAST Act of 2015, over $2 billion per year is budgeted to the Highway Safety Improvement Program to improve highway safety on public roads to achieve a significant reduction in traffic fatalities and serious injuries. Projects that will reduce losses by improving safety need to include these reduced losses in the CBA. Some significant safety considerations include

- **Loss of life.** Flooded roadways pose a safety hazard to vehicles as wheels lose contact with the road, resulting in vehicles crashing or being washed away. Adaptation projects that reduce risks from flooding and other natural hazards can help reduce loss of life. The value of statistical life (VSL) can be determined using the most current discretionary grant guidance, which is updated annually and available from the U.S. DOT Office of Transportation Policy website (https://www.transportation.gov/policy/transportation-policy). While loss of life is currently calculated only in connection to impacts to vehicles and accidents, there are loss of life implications for other transportation decisions (emissions and resulting health and safety issues); fossil fuel emissions have short-term, well-established loss-of-life impacts caused by inflammation and disease, as well as longer range impacts via climate change.
- **Injuries.** Improving passenger and pedestrian safety is a primary objective of many transportation resilience projects; other projects realize safety as a secondary benefit. For example, elevating a roadway or bridge above the predicted 100-year flood level for 2090 will not only help protect the bridge from future flood damage but it will also protect the safety of bridge users. Ultimately this safety improvement results in fewer injuries to asset and system users. The reduction in expected injuries owed to transportation resilience projects needs to be included as a benefit (loss avoided) in a CBA. In addition to the VSL, U.S. DOT publishes values for five different levels of severity of injuries and includes these values with its discretionary grant BCA Resource Guide (Table 9).
- **Property damage only from crashes.** In many cases car crashes may not injure occupants or pedestrians but do damage the vehicles involved. Transportation resilience projects could improve safety such that the number of crashes is reduced. The reduction in property damage from crashes resulting from safety improvements can be included in a CBA as a benefit (loss avoided). U.S. DOT includes a value for damage to property only from crashes in its BCA Resource Guide.

Table 9. U.S. DOT–recommended values of injuries (2018).

Maximum Abbreviated Injury Scale (MAIS) Level	Severity	Fraction of VSL
MAIS 1	Minor	0.003
MAIS 2	Moderate	0.047
MAIS 3	Serious	0.105
MAIS 4	Severe	0.266
MAIS 5	Critical	0.593
Fatal	Not Survivable	1.000

- **Delays from crashes.** Vehicle crashes often delay other transportation system users. The magnitude of the impact depends on the location, time of day, physical extent, duration of crash investigation, and number of system users at the time the crash occurs and immediately after. By improving system safety and reducing the number of crashes that occur at a site or along a corridor, system users will avoid increased costs associated with the value of their time and decreased vehicle-operating costs.

On the positive side, reduction in emissions and air quality improvements lead to health-related safety benefits. Health and safety are primary public responsibilities and health is beginning to be included in the safety mandate, to which DOTs also adhere.

Economic Impact Analysis versus Cost-Benefit Analysis

As discussed in Chapter 2, an EIA differs from a CBA in that a CBA evaluates the value of a project's benefits and costs to society while an EIA considers a project's impact on the economic activity within a locality or region. Common economic impacts include retail spending, tax revenues, jobs, and property values. EIAs typically evaluate only the positive impacts a policy or project has on a locality or region rather than the net effect. For example, an EIA will evaluate the positive impacts a transportation project has on one region, but will not take into account any adverse effects it might have on a neighboring region, nor does it consider the cost of the investment to the government (or other project sponsors). Emissions are a classic case of this discrepancy. Those living in less-desirable areas closest to high-traffic corridors also suffer the greatest health effects from emissions, controlling for other variables; people everywhere suffer from climate change impacts regardless of whether they drive and contribute to emissions through fossil fuel combustion.

Update to the Scenario

The Virginia DOT evaluated the benefits associated with implementing adaptation strategies to increase the capacity of the culvert. They identified losses that would be incurred if none of the adaptation strategies is implemented. The losses include

- Damage to physical structures,
- Increased maintenance costs,
- Debris removal and other disaster incidental costs,
- System-user delays associated with road closures, and
- Loss of fish habitat.

A summary of the losses associated with the 100-year and 500-year events is included in Table 10.

Table 10. Potential annualized losses for example scenario under current climate conditions without implementing adaptation options for the current 50-, 100-, and 500-year recurrence intervals using a 7 percent discount rate.

BENEFITS	***DAMAGES BEFORE MITIGATION - SAME FOR ALL THREE PROJECT TYPES***		
Benefit Data Input			
Event return period, T_c (years)	**50**	**100**	**500**
Associated return period, T_c	**T_{cnd}**	**T_{cmod}**	**T_{cmax}**
Associated flow, Q_c (cfs)	9,000	10,505	13,982
Assumed level of damage to culvert (%)	*0%*	*50%*	*100%*
Physical damages (culvert)	*$ -*	*$ 200,000*	*$ 400,000*
Physical damages (road)	*$ -*	*$ 400,000*	*$ 800,000*
Subtotal - Physical Damages	$ -	$ 600,000	$ 1,200,000
Traffic - one-way trips per day	*0*	*3,000*	*3,000*
Detour time (hours)	*0.00*	*1*	*1*
Detour - additional miles	*0*	*20*	*20*
Economic loss of function ($/day)	*$ -*	*$ 132,420*	*$ 132,420*
Duration of roadway loss (days)	0.0	7	14
Subtotal - Loss of Function	$ -	$ 926,940	$ 1,853,880
Clean up/debris removal	*$ -*	*$ 60,000*	*$ 120,000*
Traffic control	*$ -*	*$ 10,000*	*$ 20,000*
Casualties (injuries, loss of life)	*$ -*	*$ -*	*$ -*
Damages to vehicles	*$ -*	*$ -*	*$ -*
Subtotal - Other Damages	$ -	$ 70,000	$ 140,000
Access to salmon habitat - 2 acres	*$ -*	*$ 2,428*	*$ 2,428*
Subtotal - Environmental Impacts	$ -	$ 33,508	$ 33,508
Roundoff Adjustment (1,000)	*$ -*	*$ 1,630*	*$ 3,227*
Total Event Damages (Roundoff)	**$ -**	**$ 1,630,000**	**$ 3,227,000**

Some of these losses would be avoided if adaptation strategies were implemented under current conditions. Depending on the design level of protection, some residual damages could occur after the projects are implemented if the design level of protection is exceeded. The design level of effectiveness for climate-adapted conditions and the associated losses avoided are discussed in Chapter 7.

Data needed at this stage include

- Estimates of damages sustained from the hazard of concern,
- Estimates of additional benefits resulting from the project, separated by physical, social, and environmental benefits if using multiple discount rates, and
- Identification of any non-quantifiable benefits associated with the project.

CHAPTER 6

Conducting a Cost-Benefit Analysis

Appropriate Level of Analysis

Research suggests expecting or experiencing adverse weather events resulting in damage may be a key driver in resilience investment decisions. Yet, the majority of DOTs in the United States do not have formal criteria for determining if or when to do a CBA. Real and perceived barriers to implementing policies for completing CBAs include

- Lack of valuation information;
- Lack of baseline asset data, particularly related to actions and costs associated with extreme weather;
- Access to and confidence in using climate projections for planning;
- Difficulty computing long-term benefits;
- Concerns about the time or expense involved in performing CBAs on an asset-specific basis;
- Limited access to information on adaptation alternatives, or a decision not to consider alternatives;
- Lack of support from leadership;
- The need to integrate adaptation into the project scope and budget in the planning process (while having not done so); and
- Lack of funding mechanisms through which to implement adaptation options.

Some organizations are considering when and to what extent to conduct a CBA and are incorporating these decisions into guidance for practitioners. It may not always make sense to conduct a CBA; adaptation measures that are inexpensive to implement are unlikely to warrant a CBA, while complex, expensive projects are likely to benefit from a detailed CBA. Likewise, long-range planning and exploration of the implications of different paths will benefit from a CBA, whether it is quick and informal or more elaborate. DOTs can ascertain the financial implications of changes to the transportation system caused by continued, increasingly serious flooding and the sustainability of certain areas.

Conceptual Planning

The results of this team's research indicate that DOTs believe performing a CBA is most useful during planning activities. CBAs performed at this stage allow transportation practitioners to evaluate projects and even programs at a high level to gauge which ones are likely to be the most beneficial to pursue in greater detail. CBAs at this stage allow agencies to determine how they might allocate their capital budgets and resources to develop priorities and achieve objectives.

Detailed Study

CBAs can also be completed during the design phase of a project to determine which design alternatives or elements of a design will yield a positive ROI.

Selection of Alternatives and Analysis Time Frame

Adaptation options are needed to address identified vulnerabilities in priority investments. Adaptations may be proposed to account for factors such as risk tolerance, performance, and technical feasibility. Expert knowledge may be needed to identify appropriate adaptations and alternatives, particularly for flood impacts, though transportation-specific guidance is becoming increasingly available. Several publications and engineering design resources are shown in Table 11.

Table 11 deals predominantly with engineering adaptations applicable to the longer–life cycle assets most commonly subjected to CBAs during the capital planning process. Comparatively lower-cost, operations-focused tools may also be used as adaptations to extreme weather and changing climate. Some common techniques to handle lower-intensity "nuisance" events that nonetheless have an effect on demand and performance are summarized in Table 12.

The time horizon is the number of years that the CBA analyzes. A longer time horizon automatically gives more weight to the impacts that happen in the future. For example, if an impact happens in year 20, but the time horizon is 15 years, then it will not be included in the CBA. The overall impact on the CBA depends on whether the future impacts from a given project are mainly positive or negative. For example, a project that yields large positive values in later years will be favored by CBAs with a long time horizon.

Selection of alternatives and time frame will be interwoven with the transportation-planning process. MAP-21, the Moving Ahead for Progress in the 21st Century Act, requires state DOTs to develop transportation asset management plans (TAMPs), which include investment strategies that lead to a program of projects that would help the state achieve its targets for asset condition and performance (FHWA, 2017). As part of the planning provision of 23 CFR §450.206(c)(4), state DOTs are required to integrate the goals, objectives, performance measures, and targets of the TAMP into the statewide transportation-planning process. As transportation agencies develop their TAMPs they should consider the impact that extreme weather and climate change could have on their assets, and then develop strategies to improve the resilience of assets determined to be most critical or most at risk, programming them as appropriate into their capital financial plans. NCHRP Project 25-25(94), "Integrating Extreme Weather into Transportation Asset Management Plans" (http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP25-25(94)_FR.pdf), provides a framework for integrating extreme weather and climate change impact considerations into transportation asset management planning.

The TAMP sets the long-term infrastructure condition goals and performance targets. The state long-range transportation master plan sets the long-term transportation plan and improvements for the state. The state transportation improvement plan (STIP) is the shorter-term project planning and budget document that reflects the DOT's long-term strategic plan and TAMP. The TAMP should be consistent with the statewide plan and the STIP. TAMPs should be integrated into the planning processes that lead to the STIP (FHWA, 2017). STIP budgets are constrained, meaning that the total cost of projects cannot exceed the funds available. The state coordinates with metropolitan planning organizations and councils of governments to incorporate some of their transportation improvement plan projects into the STIP based on the consistency of the transportation improvement plan projects to meet the state's performance targets and other TAMP goals. Many states are taking steps to incorporate climate change and adaptation performance measures into their updated STIPs.

Because TAMPs are high-level, long-term documents, it is unlikely that CBAs will be performed as part of the TAMP development process. Rather, CBAs can help inform the selection of projects for funding in the STIP within the framework of the TAMP, particularly as project alternatives

Table 11. Engineering design publications and resources.

Resource Title	Author/ Organization	Modes	Links
Synthesis of Approaches for Addressing Resilience in Project Development (2017)	FHWA	Multimodal /Multi-Asset	https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/teacr/index.cfm
"Planning for Systems Management and Operations as Part of Climate Change Adaptation" (2013)	FHWA	Operations	http://ops.fhwa.dot.gov/publications/fhwahop13030/
HEC-17: "Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience" (2016)	FHWA	Roadway Bridge Railway Structure Tunnel	https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf
HEC-25: "Highways in the Coastal Environment: Assessing Extreme Events" (2014)	FHWA	Roadway Bridge Railway Structure Tunnel	http://www.fhwa.dot.gov/engineering/hydraulics/pubs/nhi14006/nhi14006.pdf
"Integrating Extreme Weather Risk into Transportation Asset Management" (2012)	AASHTO	Multi-Asset	http://climatechange.transportation.org/pdf/extrweathertamwhitepaper_final.pdf
NCHRP Report 750: Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report **(2014)**	NCHRP	Multi-Asset	http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_750v2.pdf

(continued on next page)

Table 11. (Continued).

Resource Title	Author/ Organization	Modes	Links
NCHRP Project 15-61, "Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure"	NCHRP	Multi-Asset	https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4046

Table 12. Examples of adaptation using lower-cost, operations-focused tools and activities.

Operational Impact Area	Example Tools or Activities	Adaptation Examples
Debris Management	• Personnel scheduling	• Perform more frequent inspections • Clear culverts and drains before forecasted events (Drenan and Treloar, 2014)
Procurement and Preparedness	• Training • Operations plans • Interagency coordination	• Cross-train staff to handle multiple aspects of event response • Reserve equipment (e.g., buses) for evacuation or other response and preparedness responsibilities • Reserve sufficient materials for "bad seasons" with multiple extreme events • Establish contingency contracting to maintain surge capacity for events occurring outside typical seasons (FHWA, 2016)
Monitoring	• Road weather information system stations • BridgeWatch water-level monitors • U.S. Geological Survey and National Weather Service stream gauges	• Invest in denser networks of real-time road weather monitoring • Receive, respond to, and communicate changes in conditions • Anticipate response activities such as closures and detours (*Highway Capacity Manual,* 6th ed., 2016)
Communication and Intelligent Transportation Systems	• Variable message boards • Dedicated radio • Social media • Independent agency communication system	• Apprise travelers of real-time and expected extreme weather conditions and changes in traffic conditions • Reduce disruptions to agency communications during events (G. Donaldson, personal communication, March 22, 2016)

are evaluated to meet the TAMP's extreme weather– and climate change–related goals. Figure 18 suggests how CBA can be incorporated into the planning process to help meet the TAMP's and STIP's goals.

Some states are going so far as to institute policies that mandate incorporating climate change into long-term planning processes and implementing cost-effective adaptation approaches. For example, in accordance with Executive Order 41, the State of Delaware is incorporating climate change adaptation into its planning processes. The executive order requires all state agencies to incorporate cost-effective measures for adapting to increased flood levels and sea level rise to minimize risk. Planning for sea level rise is to be done in accordance with the levels established by the state's Department of Natural Resources and Environmental Conservation. The department is revising its LCCA procedures to account for climate change and working with the Delaware DOT as it evaluates the costs and benefits of certain adaptation measures and develop guidance for incorporating CBAs into transportation-planning processes.

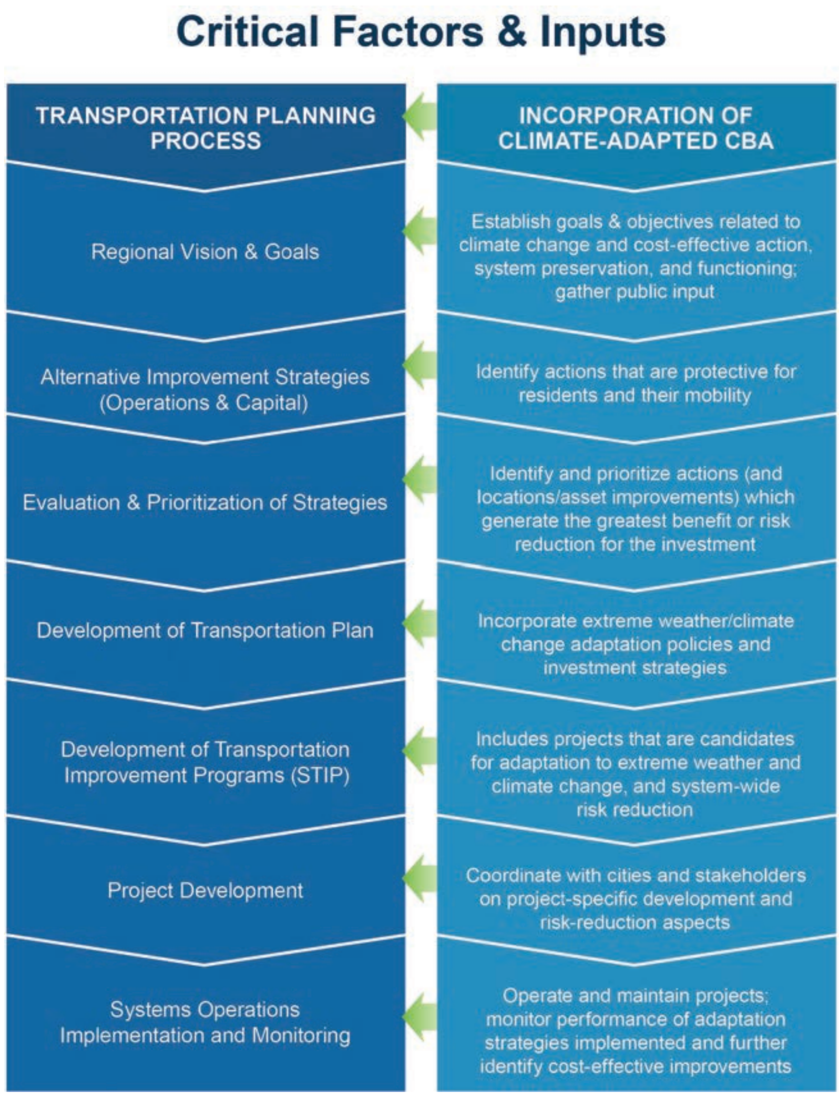


Figure 18. CBA can be incorporated throughout the transportation-planning process to evaluate cost-effectiveness of climate and extreme weather adaptation.

Recurrence Intervals

The recurrence intervals (RIs) of natural hazard events such as floods have to be determined and associated with levels of corresponding damages and losses to enable evaluation of the impacts of climate adaptations using CBA. The RI of an event is defined as the expected return period (T) of an event expressed in years. Flood-event RIs are inversely related to annual probabilities of flood events. For example, a flood event with 1 percent annual chance or a 0.01 annual probability of being equaled or exceeded in any given year has an RI equal to (1/0.01) = 100 years; while a 10 percent annual chance or 0.10 annual probability flood event has an RI equal to (1/0.10) = 10 years.

RIs for historic events can be determined based on other past events or through hydrologic analysis:

- **Flood elevations or discharges tied to flood RIs.** Flood elevations or discharges from historic events can be estimated by comparing them with flood elevations or discharges of events with known RIs.

  Historic event elevations or discharges can be found by reviewing stream or tide gauge data from the U.S. Geological Survey (USGS) website (https://waterdata.usgs.gov/nwis/sw) and selecting the gauge data closest to the project site. Additionally, the USGS PeakFQ Program, which can be downloaded from the USGS website (https://water.usgs.gov/software/PeakFQ/), can provide identified flood RI data. Section 2.1.2 of FEMA's Supplement to the Benefit-Cost Analysis Reference Guide (https://www.fema.gov/media-library-data/1396549910018-c9a089b8a8dfdcf760edcea2ff55ca56/bca_guide_supplement__508_final.pdf) provides step-by-step instructions and a detailed example of estimating RIs using the USGS PeakFQ approach.

  FEMA Flood Insurance Study (FIS) Profiles and Discharge Tables or Transects provide flood elevations and discharges for the 10-, 50-, 100-, and 500-year RI flood events. FIS data are available for all communities participating in the National Flood Insurance Program from the FEMA Map Service Center website (https://msc.fema.gov/):
  - From the menu on the left select "Search All Products."
  - From the drop-down menus select the state, county, and community of interest and then press "Search."
  - Select "Effective Products" and then "FIS Reports."
  - Download the file containing the desired flood insurance study.

  Following large events like Hurricane Katrina (2005) or Hurricane Sandy (2012), FEMA may prepare Advisory Base Flood Elevations and preliminary Flood Insurance Rate Maps (FIRMs) before issuing new FIRMs. In other cases, hydraulic and hydrology studies may be used when FIS data may be incomplete or out of date, but complete copies of studies need to be provided as supporting documentation.
- **Hydrologic analysis.** RI determinations made by a hydrologist or other qualified expert may be considered for use in a specific geographic location, especially for large events such as Hurricane Katrina (2005) or Hurricane Sandy (2012). Documentation sources include
  - Post-event studies prepared by the U.S. Army Corps of Engineers or the USGS; grant applications must include complete copies of studies.
  - Estimates prepared by a hydrologist; grant applications should include background data, calculations used to estimate RIs, or both.

  The RIs of major storm events can vary significantly depending on the location. This variation is illustrated in Figure 19, which shows the results of a January 2013 analysis report prepared for FEMA to estimate storm-surge flood recurrence intervals of Hurricane Sandy in New York and New Jersey.

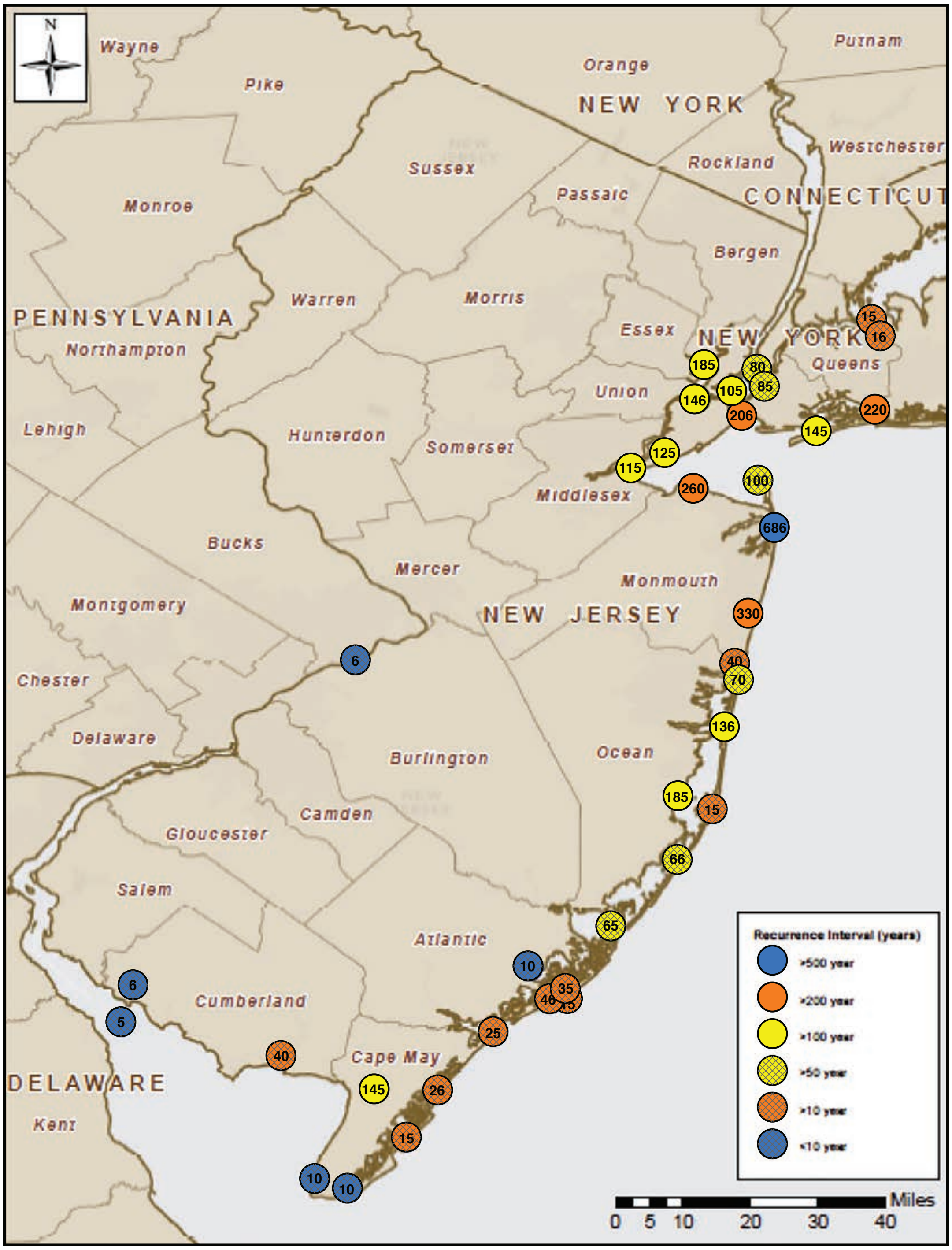


Figure 19. Estimated coastal flood recurrence intervals for Hurricane Sandy in New Jersey and New York (FEMA, 2013b).

- **Climatological or rain gauge data.** Since a 100-year rainfall event does not usually equate to a 100-year flood, climatological or rain gauge data for historic damage events need to be tied to flood RIs by a hydrologist or other qualified professional. Sources include
  - The National Climactic Data Center Storm Events Database (https://www.ncdc.noaa.gov/stormevents/), which records daily rainfall and other climactic data recorded by thousands of weather stations nationwide. Grant applicants need to remember to include all applicable data.
  - The National Climactic Data Center also has records available online (https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00313).
  - Analysis of rain gauge data prepared by a hydrologist. Grant application documentation should include background data, calculations used to estimate flood RIs, or both.

If the RIs for historic flood events are unknown and cannot be established using the approaches described previously, some tools such as the FEMA BCA Tool (https://www.fema.gov/benefit-cost-analysis) and FTA HMCE Tool (https://www.transit.dot.gov/funding/grant-programs/emergency-relief-program/hazard-mitigation-cost-effectiveness-tool) feature an unknown recurrence interval calculator that can be used to estimate unknown RIs. Use of the unknown recurrence interval calculator requires

- A minimum of three hazard events occurring in different years in which either
  - The RIs of all events are unknown, or
  - The RIs of up to two events are known and have total damage values that exceed the total damage values of all the other unknown RI events.
- An analysis duration based on the age of the structure (year built) or a minimum of 10 years, whichever is greater.

Additional information regarding the use of these calculators and their required inputs is included in Appendix F.

For some projects, particularly those projects that will construct a new facility or a facility in a new location, historic data regarding damages sustained from an event might not be available. In these cases, damages that might be expected from an event having a certain magnitude and recurrence interval can be estimated from studies by engineers or other qualified experts. Recurrence intervals need to be calculated for expected flood events. Approaches for estimating recurrence intervals are as follows:

- **Estimated event RIs from engineering studies.** Engineering studies or reports from qualified experts may be used to estimate RIs of various hazard events. Information sources include
  - Engineering Reports, a good source to indicate various estimated event RIs to various transportation facilities based on similar historic events or detailed engineering analysis.
  - Transportation Agency Studies, which can indicate estimated event RIs affecting transportation facilities; these would likely include hydrologic and hydraulic studies completed by agency engineers.
- **Estimated event RIs based on the FEMA BCA Tool.** The FEMA BCA Tool can be used to estimate flood-event RIs as a function of flood depth based on the FIS or equivalent hydraulics and hydrology data. These estimates can account for sea level rise but do not account for other changes in climate:
  - FIS profiles and discharge tables or transect data are available from the FEMA Flood Map Service Center website (https://msc.fema.gov/portal/home).
    - From the menu on the left select "Search All Products."
    - From the drop-down menus select the state, county, and community of interest and then press "Search."
    - Select "Effective Products" and then "FIS Reports."
  - When available, preliminary FIS or hydraulics and hydrology studies may be used where effective FIS data may be incomplete or out of date.

Base and Alternative Cases

Often in BCA, a "base case" is analyzed first for comparison of alternatives. The base case is not a "do-nothing" alternative. "Do-nothing" assumes that the asset will be left as is and will not be regularly maintained or periodically upgraded over its useful life. Because DOTs develop and implement maintenance and repair schedules for transportation assets, a business-as-usual case is assumed to be the "base case." The base case assumes that the agency maintains its regular O&M practices over the time frame of the alternatives that will be analyzed. This business-as-usual analysis assumes that the agency's usual processes will be followed with respect to the asset, project, or program being analyzed.

Complex Projects with Sub-Projects or Incremental Projects

Changing climate conditions will require transportation engineers to adapt to a new normal and account for extremes that did not previously need to be managed, or to put it another way, they will need to treat as average events that were once extremes. These changes could necessitate that designers and engineers plan for transportation infrastructure in a more incremental fashion, that is, using an adaptive management approach. For example, one option for a bridge design is to construct it to one elevation and then elevate it 30 years later to accommodate additional flows that arise from climate change. In so doing, designers are able to bide their time, allowing more science to emerge on climate change predictions in the longer term, while also constructing something of value for society in the near term.

How does this incremental approach affect the CBA? First, the designer needs to establish the base case, as discussed previously. For the bridge example, the base case could be a bridge with a designed life span of 50 years that is not designed to be elevated in the future; that is, this project is not designed with the impacts of climate change in mind.

- **Alternative 1.** Once the base has been established, a comparison can be made. For the bridge example, the initial comparison option could be to assess the incrementally funded bridge, that is, one that is designed with plans to elevate it in the future.
- **Alternative 2.** Another design alternative to compare could be for a bridge designed to be large enough from the beginning to withstand the future impacts of climate change; essentially, it would be a pre-elevated bridge.

Once the base case and alternatives are established, the design team would need to estimate how much each design would cost to construct. The base case bridge in the example is probably the cheapest to construct, with Alternative 1—the incremental option—being costlier because it embeds more complicated design elements from the beginning. Alternative 2 is likely the most expensive of the three designs, as it is the largest. The Alternative 1 design element—the bridge being elevated at year 30 to cope with the predicted impacts of climate change—is then factored in. To assess this in the BCA, the expected cost, including costs to commuters from delays and detours, needs to be input. These values will be discounted to generate the elevation's present value.

Operations, maintenance, and disposal costs or salvage value can also be estimated. In the bridge example, it is difficult to say that the three hypothetical designs would have significantly different O&M costs in terms of road repair and typical structural maintenance. Similarly, the annual benefits generated by travel time savings, and so on, may also be assumed to be similar.

Depending on how the bridge is financed, there may be some differential debt financing costs. For example, if the bridge will be partly or wholly financed through a loan or bond, the more expensive project will have correspondingly higher interest repayments.

In this analysis, the BCA needs to account for alternatives analyzed over a term equal to at least the longest-lived asset across the alternatives (and base case), which is how replacement costs for shorter-lived alternatives are taken into account. Alternatively, salvage value, value beyond the term of the analysis, or both can be included as an annuity.

Overall, it is assumed that, excluding the elevation construction of the incremental bridge, the three bridges may perform similarly through their operational phases, without factoring in climate change. However, once the annualized expected impacts from climate change are included in the BCA, the options may start to diverge in terms of their BCR.

- Base Case
  - The design team needs to estimate the annualized expected damages resulting from climate change. This process is described in Chapter 5, but it essentially entails establishing the return period of a flood for which there would be varying levels of damage, ranging from no damage through to bridge failure, calculating the damages from each of those return periods, and estimating the likelihood of those, given climate predictions.
  - Because the bridge is not designed to be elevated, the annualized expected damages and costs will be higher for this design. This is because increased flows or sea level rise resulting from climate change will cause damage sooner, more often, and at greater intensity.
  - The design team needs to include not only the direct costs from repairs and reconstruction but also the indirect costs from road closures. Indirect costs include increased travel time for commuters, which may be more significant versus direct repair costs for smaller climatic impacts.
- Alternative 1
  - Before the elevation is undertaken, the annualized expected costs between Alternative 1 and the base case are likely to be similar, as their height or capacity is not significantly different.
  - However, once the elevation is complete, the "new" bridge is far more resilient to climate change than before, and the risk of damage decreases greatly. With this reduced risk of damage and failure, the annualized expected damages correspondingly decrease.
- Alternative 2
  - For Alternative 2 (the bridge designed to be large enough from the beginning), the expected annualized costs will be less than both the base case and Alternative 1 (before elevation). This is because it is able to withstand greater flows without being damaged in the process, meaning that it takes an event with a larger return period to generate damages.
  - However, the annualized expected damages may be assumed to be similar to Alternative 1 post-elevation, as they both now have similar capacities.

Whereas the base case bridge may have a higher risk of damage, closure, or even failure, Alternative 1 and Alternative 2 do not face this risk to the same degree. It is important not to double-count at this point. The initial bridge faces definite monetary costs in CBA, but avoiding those costs is not necessarily included as a benefit in the alternative designs' CBAs. This is because the benefits of the alternative bridges are already shown by the base case bridge having a cost. For example, the base case bridge may incur an annual cost of $10,000 in damages. This will already affect the comparison of the CBAs in favor of the two alternatives. If annual benefits of $10,000 in "avoided costs" are then added to the elevated bridges' CBAs, the difference will be reflected as $20,000 per year, rather than $10,000, and would double-count the annual cost and the benefit. Often in CBA, the $10,000 in avoided damages would be included as a losses-avoided benefit rather than a cost.

Sea Level Rise or Change

A potential long-term consequence of climate change is sea level rise or change. Changes in sea levels occur slowly over time from a combination of melting glaciers and thermal expansion of sea water as it warms (NOAA, 2017). NOAA (2017) estimates that the global sea level is rising at a rate of 3.4 millimeters, or just over 1/8 inch, per year. Sea level change is not uniform everywhere; some locations experience sea level increases in excess of the global average, while other locations are experiencing decreases in sea levels. Before incorporating SLR into an adaptation project, planners need to evaluate a location for SLR to determine if adaptation will be incorporated into a project. The U.S. Army Corps of Engineers circular 1165-2-212 (https://web.archive.org/web/20160519022621/http://www.corpsclimate.us/docs/EC_1165-2-212%20-Final_10_Nov_2011.pdf) and regulation ER-1100-2-8162 (http://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/ER_1100-2-8162.pdf) outline a procedure for evaluating locations for incorporating SLR adaptation into projects.

If planners determine that adaptation for SLR is to be included, the effects of a gradual change over time will be evaluated to determine if they effect changes to O&M over the life of the project (MaineDOT, 2014). With a project that addresses gradual changes, accounting for annual maintenance and repairs from damages and traffic impacts over the period considered will provide an accurate assessment of preventable losses. Accounting for dynamic costs incurred over the useful life of a project subjected to SLR needs to be considered when calculating life-cycle costs.

Extreme Heat

Throughout most of the United States, temperatures in the future are expected to be higher and the number of hot days per year is expected to increase. Heat events are measured differently from flood events in that recurrence intervals generally have not been associated with extreme heat. Extreme heat is generally defined as temperatures that hover 10 degrees or more above the average high temperature for the region and last for several weeks. It is evident from this definition that the temperature associated with extreme heat will vary based on geography, and therefore extreme heat is locally defined. For example, the average high temperature in July in Bozeman, Montana, is 83°F, while in Tucson, Arizona, the average high temperature in July is 101°F.

Extreme heat will likely have an impact on both transportation assets and construction and maintenance personnel. The potential impacts of extreme heat on paved roads, bridges, and buildings are summarized in Table 5 in Chapter 3. As with the variability in the definition of extreme heat based on local conditions, the impacts of extreme heat on some transportation assets will also vary based on materials. For example, the asphalt binder used in paving might perform differently depending on the pavement design. Generally, though, pavement binder may exhibit sensitivity beginning around 108°F (West et al., 2010). High ambient temperatures reduce the stiffness of asphalt, making it more prone to rutting (deformation) under traffic loads (Manolis, 2014). As the number of extremely hot days and the number of consecutively hot days increase, paved surfaces are likely to experience increases in rutting caused by asphalt deformation, which in turn is likely to increase O&M costs. In addition to asphalt deformation, bridges might also be affected by extreme heat at bridge joints, although Hagedorn (2016) concluded that large variations in daily temperature are more critical to bridge performance than extreme heat. As extreme temperatures and temperature variations become of greater concern for designers, different materials or design approaches may be considered. In the meantime, existing structures may require more frequent maintenance and repairs as components such as joints wear more quickly.

Similarly, extreme heat is likely to affect some of the systems in DOT buildings. Extreme heat could increase the loads placed on building cooling systems, requiring them to work longer over the course of a year. Depending on the type of cooling system, increased operating costs from electricity and water use may result. Because the systems are working longer, they may require more frequent maintenance. Further, the systems' useful life may be shorter than in the original design if it did not incorporate increased loads placed by increases in extreme heat. Increased system operating times might also increase GHGs released to the atmosphere; potential environmental impacts need to be considered when data are compiled for a CBA.

While transportation physical assets are likely to be affected by extreme heat, literature indicates that the greatest impact will be on human assets. Worker health and safety will be an increasingly important consideration when planning construction and O&M activities during hot months. Workers who work during the day will require more frequent breaks to protect them from the impacts of heat (e.g., heat stroke, heat exhaustion). Depending on local conditions, some activities normally performed during the day may need to be performed at night during periods of extreme heat. These changes in how work is performed are likely to affect project life-cycle costs and need to be factored into analyses.

In urban areas and some small cities and suburban locations, the impacts of extreme heat may have even greater impacts on transportation project costs and implementation than in more rural areas because of the urban heat island effect. These highly developed areas tend to have less vegetation and more asphalt and roofs, which absorb more of the sun's energy, leading to higher temperatures. Heat islands have higher daytime temperatures and less nighttime cooling than rural areas; temperatures in urban areas can be 1.8°F to 5.4°F higher than their surrounding areas during the day, and as much as 22°F higher at night because the built environment retains the heat absorbed during the day (U.S. EPA, 2016b). The urban heat island effect and its potential impacts on transportation projects should be taken into consideration during planning. Data for CBAs need to consider the impacts on O&M and life cycle, as well as potential environmental and social impacts.

As stated previously, traditional approaches to conducting CBAs based on recurrence intervals are not applicable to extreme heat events because they are measured differently, and the measurement is localized. Because extreme heat is a new consideration, little in the literature addresses conducting CBAs for extreme heat events. Quantifiable information is becoming available regarding the potential impacts on human health and safety, but little information is publicly available that allows extreme heat impacts on transportation assets to be quantified. Transportation agencies first need to determine which question to ask:

- Are agencies most concerned with operational impacts and costs, such as increases in energy use and the associated costs from increased demand for cooling, decreases in asset useful life, and so on?
- Are agencies most concerned about continuity of operations and the potential length and frequency of interruption if the power grid has stability issues during excessive demand?

Once a DOT determines which question it is most concerned with, it will need to evaluate the level of acceptable risk—can the function go off-line for a while, and if so, for how long? If not, how can long-term functionality be ensured?

Absent recurrence intervals, the "what-if" scenario approach might be one effective way of evaluating adaptation strategies; DOTs might ask, "What will happen if our region experiences 10 consecutive extremely hot days? What if the number increases to 25 days? 40 days?" The strategies developed can be evaluated in these contexts for costs and benefits. Because CBA methodologies for extreme heat are still in development, some cities are not seeking to quantify the impacts of adaptation strategies in terms of NPV or BCR, but rather in more qualitative terms of high, medium, and low levels of likely cost-effectiveness.

If DOTs are most concerned with operational impacts, the question of heat differences can possibly be addressed, but the potential accompanying change in humidity (e.g., future climate conditions that are both hotter and wetter) is not as easily addressed. Heating degree days and cooling degree days traditionally used in engineering design can be estimated in the future to reflect possible extreme heat events, while accounting for humidity is more difficult because wet and dry bulb temperatures are not readily available in a format architects and engineers can use. In an attempt to address this concern, the Transportation Engineering Approaches to Climate Resilience project conducted a case study in Texas to evaluate the impacts of changes in temperature and moisture on transportation asset performance. The study used the Thornthwaite Moisture Index, a dimensionless measure that indicates the humidity or aridity in a geographic region as a predictor of changes in humidity. The project study correlates the Thornthwaite Moisture Index with the various RCP scenarios in CMIP5 through 2100. These data could allow transportation practitioners to anticipate asset performance under changing temperature and precipitation and hence humidity conditions so they can determine if they will consider different design approaches, such as using a different asphalt binder in roads to decrease asphalt pavement rutting.

Life-cycle costs can be computed based on scenarios to evaluate the impacts of extreme heat on transportation assets and potential adaptation options and the results compared to evaluate cost-effectiveness. However, traditional benefits are more difficult to quantify. If the question of concern relates more to continuity of operations, an EIA of an asset or system outage could be useful to DOTs in making decisions regarding adaptation for extreme heat.

CHAPTER 7

Study Level 1 Climate Resilience Cost-Benefit Analysis

Introduction to Levels of Analysis

Historically, many DOTs have used CBA only for large or complicated projects; however, with increased emphasis on asset management planning, transportation practitioners increasingly recognize that CBA would be useful in design and planning. They also realize that CBA could be applied to a betterment decision on an FHWA ER project, but CBA is generally regarded as cumbersome and costly, and transportation practitioners are reluctant to undertake the analysis for decisions regarding smaller capital projects. Yet, changes in weather and climate patterns are influencing assets designed for smaller events. More frequent significant rain events and increases in sea levels are resulting in increased incidents of nuisance flooding, causing transportation assets to be inundated more frequently. Transportation practitioners need a short and simple method to evaluate if adaptation strategies will be considered, and if so, what level of investment might be cost-effective.

Chapters 7 and 8 describe an approach for conducting an initial screening to evaluate if adaptation strategies might be cost-effective, and if implemented, what level of damages might be expected with and without adaptation. The focus of climate change impacts considered in this methodology is on the increased design flood discharges for transportation facilities, including culverts, bridges, and stormwater control facilities. The general assumption is that the relationship between discharges and their frequency (i.e., return interval) for current conditions is based on a historically stationary hazard, while future values may be subject to non-stationarity brought about by climate change. The discussion that follows focuses on riverine flooding, but it is independent of flow rates or water surface elevations, so can be equally applicable to riverine or coastal analysis.

The design criteria commonly used for transportation facilities, including drainage work and flood control projects, is based on annual exceedance probability and its reciprocal, the return period. Table 13 summarizes the design criteria most transportation agencies use. The value of annual exceedance probability or return period for each design level represents an acceptable level of risk at that level.

Although design discharges and flood levels may increase under climate change scenarios in comparison with current conditions, facilities do not necessarily need to mitigate against events with larger return periods. It simply means the same return period (same failure probability) will feature higher discharges and flood elevations. While the potential damages associated with a specific flood discharge will not change in the future, the overall hazard level will increase if the same discharge will occur more frequently (i.e., will have a smaller return period) (Figure 20). Ensuring the system will accommodate the increased discharges will make it resilient against the impacts of climate change, but attempts to adapt to climate change impacts need to be balanced with approaches that make economic sense. In some

Table 13. Design criteria example for annual exceedance probability (AASHTO, 2014).

Roadway Classification	Annual Exceedance Probability (percent)	Return Period (years)
Interstate, Freeways (Urban/Rural)	2%	50
Principal Arterial	2%	50
Minor Arterial System, ADT>3,000 VPD	2%	50
Minor Arterial System, ADT≤3,000 VPD	4%	25
Collector System with ADT>3,000 VPD	4%	25
Collector System with ADT≤3,000 VPD	10%	10
Local Road System	20%–10%	5–10

ADT = average daily traffic. VPD = vehicles per day.

cases, designing for the absolute worst case scenario might not be cost-effective, as discussed in Box 3.

Flooding is one of the most frequent and costliest natural hazards to damage transportation assets and systems, as well as one of the natural hazards likely to be most affected by climate change; average annual flood losses in the five most at-risk cities in the United States are expected to be approximately $8 billion by 2050 (Hallegatte et al., 2013). Consequently, this CBA methodology focuses on flooding. The CBA analysis levels follow the approach taken in HEC-17, "Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience," which provides technical guidance and methods for assessing the vulnerability of transportation facilities to extreme events and climate change in riverine environments. The focus in HEC-17 is quantifying exposure to extreme flood events, considering climate change and other sources of

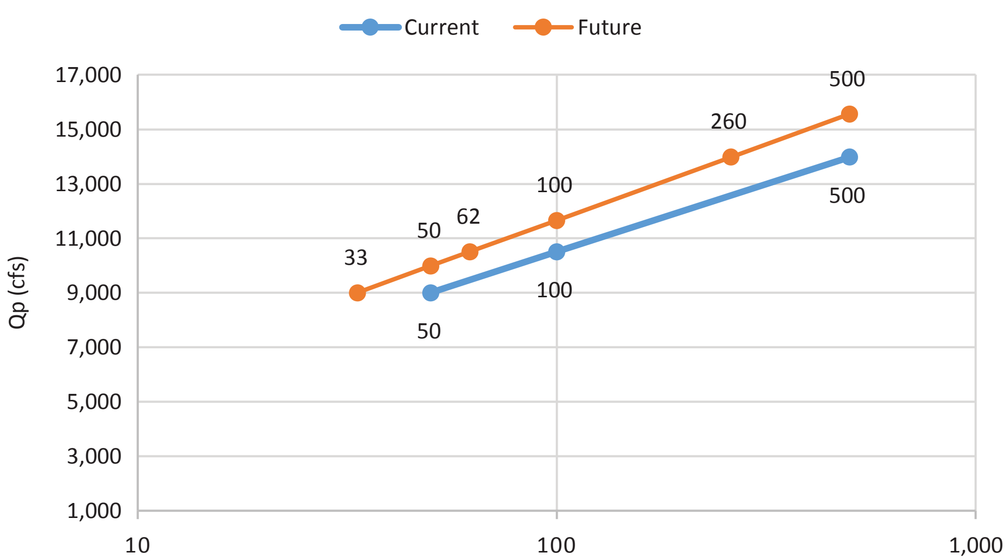


Figure 20. Climate change could result in a given level of an event occurring more frequently in the future.

Box 3. MaineDOT Culverts

Maine looked at two inland corridors and the crossings involved, considering culvert and bridge sizing for extreme events. It used the ECOS tool to do CBA on two to three structures per corridor, along with depth-damage functions. Surprisingly, the most efficient solution in terms of cost/choice was the 25-year storm sizing. The 100-year storm has been a default upgrade/adaptation in the past. MaineDOT's study used five different sizing scenarios, starting with a 25-year storm, a 100-year storm, then plus 25 percent, plus 50 percent, and 1.25 bankfull. It found that 25-year storm sizing could handle the amount of water generated in this watershed and that there were risks to a larger structure that might hold back more water. MaineDOT decided it was cheaper to replace the riprap, clean the corridor, and replace the pipe, as the modeled storm would not damage the road structure (MaineDOT, 2015).

non-stationarity. HEC-17 offers five levels of analysis with increasing complexity and accuracy for estimating the future discharges:

1. Historical Discharges,
2. Historical Discharges + Confidence Limits,
3. Precipitation Projection Trend Test,
4. Projected Discharges using CMIP tool, and
5. Customized Projected Discharges with Climate Scientist.

HEC-17 Levels 1 and 2 are simple analyses, resulting in an amplified design discharge.

HEC-17 Levels 3, 4, and 5 are more complex analyses, resulting in amplified discharges for each return period that are calculated to account for climate change:

- **HEC-17 Level 3** is a transition level that involves T-year, 24-hour precipitation projection using various CMIPs, which may result in staying with Level 2 (if the trend is weak) or moving to Level 4 to compute future discharges using future precipitation (if the trend is strong).
- **HEC-17 Level 4** involves incorporating rainfall projections into rainfall/runoff hydrology. It could be as simple as using future mean annual precipitation in a regional discharge regression equation or as complicated as using projected rain and temperature in a full hydrologic model.
- **HEC-17 Level 5** is an advanced version of Level 4, which is only appropriate for larger, costlier projects or infrastructure and requires expanded expertise in hydrologic modeling, climate science, and land use planning for custom, site-specific projections.

This guidebook focuses on HEC-17 Levels 1, 2, and 3, which are the levels of analysis most likely to be completed for planning or comparison of design alternatives. Approaches for HEC-17 Levels 4 and 5 analyses are probabilistic and robust; they require the generation of peak flow using Monte Carlo simulations, determination of the flood elevation resulting from the generated peak flow, estimation of the flood cost for each event when the elevation overtops the low point of the roadway, and calculation of the flood cost savings for each improvement option. These approaches appear to be reasonable and robust, but DOTs may generally consider them too complex and time-consuming for making funding decisions during the planning and design alternatives analysis phases. In this guidebook, *HEC-17 Level* refers to the level of analysis defined during this study and described in Chapters 7 and 8.

Process Walk-Through with an Example for Riverine Flooding

Select Data Inputs and Data Sources

Parameter	Value Used in Scenario	Data Source(s)
Facility of concern	Culvert	Project file
Geographic location of the facility/corridor under consideration	Chesterfield, VA	Site plan, maps
Hazard(s) of concern	Flood	Hazard analysis
Current design criteria—flow rate	9,000 cfs	Engineering designs and plans
Current design criteria—recurrence interval	50-year event	AASHTO design manual, DOT design manual
Discount rate(s) to be used in the analysis	7%	OMB A-94
Expected useful life of current facility	Less than 2 years	Capital plan, O&M records
Expected useful life of replacement facility	50 years	Virginia DOT design guides
Anticipated time frame for implementation of adaptation strategies	Less than 2 years	Capital plan
Scenario(s) to be used for analysis	Precipitation conditions in 2049	NOAA Atlas 14, SWMM-CAT for warmer, wetter conditions 2045–2075
Design concepts of adaptation strategies	Enlarge culvert, add multiple culverts, use box or arch culvert	Engineering department
Cost estimate for each adaptation strategy (life-cycle costs, including any long-term adverse impacts from the adaptation strategy)	Cost estimates	Historical data, recent bids for similar work, cost-estimating software
Identification of any non-quantifiable costs associated with the project	None	DOT analysis
Estimates of damages sustained from the hazard of concern	Loss estimates	Historical data, engineering analyses, O&M records, depth-damage curves
Estimates of additional benefits resulting from the project, separated by physical/social/environmental if using multiple discount rates	Benefits estimates	FEMA benefit-cost analysis tools for drought, ecosystem services, and post-wildfire mitigation
Identification of any non-quantifiable benefits associated with the project	None	DOT analysis

Establish Base Conditions

Study Level 1 analysis is basically an approximate test to see if it would be cost-effective to upgrade the hydraulic structure for the future conditions posed by climate change. The central point in this approach is that a given discharge, Q, will cause a given level of damages, D, with or without climate change. However, considering climate change, the given discharge of Q may have a smaller return period in the future than its current value, that is, the same flow, Q, will occur more frequently in the future than it does now, resulting in the level of damages, D,

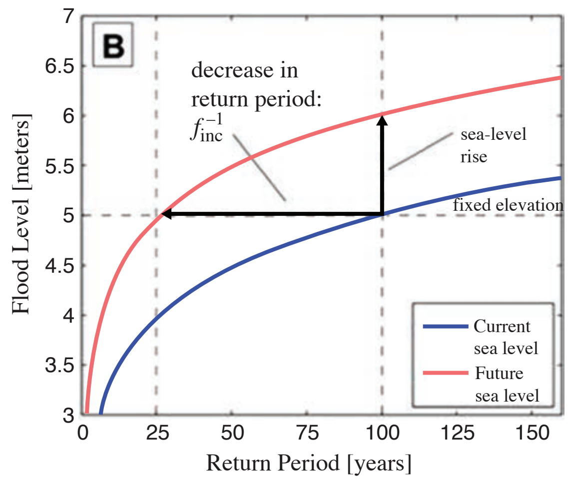


Figure 21. Climate change and sea level rise will result in flood events of a given magnitude occurring more frequently in the future (after Vitousek et al., 2017).

occurring more often (Figure 21). Therefore, the goal of a Study Level 1 analysis is to identify how to improve the performance of the hydraulic structure or the resilience of the roadway, so that for a given return period the future flow, Q', under climate change conditions has the same return period as the current flow, Q, so that the level of damages, D, is approximately the same in the future for the higher discharge rate as it is now for the current discharge rate. For damages to remain the same in the future, the improved structure needs to accommodate the additional discharge. The basic premise for this analysis is that even though the relationship between frequency and discharge changes with time, the relationship between frequency and damages remains somewhat constant (e.g., damages sustained from a future 50-year event under changing climate conditions are the same as damages for a 50-year event under current conditions).

This approach assesses damages for three event categories: (1) medium probability, low consequence (i.e., base case), (2) low probability, medium consequence, and (3) very low probability, very high consequence, as summarized in Table 14.

The following steps summarize the basic inputs and calculations required for this approach. It is intended to be simple enough to calculate by hand, although use of a computer spreadsheet program such as Excel will make calculations easier. This approach uses several variables; a summary of the variables used and their meanings is included in Table G-1 in Appendix G. A blank worksheet to complete a Level 1 analysis by hand is included in Appendix I. A list of sources where needed data might be found is included in Appendix J.

In the steps below, the approach is applied to an example to demonstrate its use. The example is based on data for Chesterfield County, Virginia, using rainfall data from NOAA Atlas 14 for the watershed. Future discharge flows were calculated using the EPA's SWMM-CAT model. However, other approaches can be used to calculate future discharges; some suggested methods

Table 14. Event categories most likely for application of a Level 1 analysis.

	Low Consequence	Medium Consequence	Very High Consequence
Very Low Probability			X
Low Probability		X	
Medium Probability	X		

are included in HEC-17, Chapter 7, such as Rational Method, Unit Hydrograph, and the Natural Resources Conservation Service's Peak Graphical Method.

1. Identify the largest return period for which there will be no damages. Typically, this is the design return period. Typical design return periods for transportation hydraulic structures are 10, 25, or 50 years depending on road classification (Table 13). This is T_{cnd}. For example, if a bridge is designed to safely pass the 50-year discharge, T_{cnd} would be 50 years.
2. Identify a return period associated with an event that would cause moderate but considerable structural damage or roadway flooding and traffic interruption. Typically, this would be the next-highest standard return period to T_{cnd}, defined as T_{cmod}. For the bridge designed to a 50-year profile, T_{cmod} might be set to 100 years.
3. Identify a return period for which damages would be practically maximized. Larger or more significant events might cause greater damages, but their probabilities are so small that they do not add much overall risk. This maximum, realistically occurring return period is T_{cmax}. For example, for the bridge designed to 50 years, T_{cmax} might be the 500-year flood, which causes bridge structural failure, road embankment erosion, and loss of roadway function for several weeks or months.
4. Estimate total damages associated with T_{cmod} and T_{cmax}. Typical damages, D_{cmod}, at the T_{cmod} level, could include loss of riprap, short-term road closure, traffic control and road cleanup costs, and so on. Typical damages, D_{cmax}, at the T_{cmax} level could include the failure of the hydraulic structure leading to large structural damage and loss of road service and possibly injuries or fatalities. These damages may be estimated based on historical damage records for the same or similar structures or based on expected damages assessed by engineers. The damages are stated in terms of constant dollars by applying the appropriate present value interest factor (Appendix B). For this example, assume D_{cmod} is equal to $1,630,000 and D_{cmax} is $3,227,000.
5. Use Equation 10 to calculate the expected annual damages between T_{cnd} and T_{cmod}. Annual damages are the damages expected per year over the life of the asset or corridor, or the useful life of the adaptation project. "Expected" annual damages does not mean that these damages will occur every year.

Equation 10. Calculating expected annual damages for an event of moderate damage in a Level 1 analysis.

$$D_{acmod} = \frac{D_{cnd} + D_{cmod}}{2} * \left(\frac{1}{T_{cnd}} - \frac{1}{T_{cmod}} \right)$$

For the example,

$$D_{acmod} = \frac{0 + 1{,}630{,}000}{2} * \left(\frac{1}{50} - \frac{1}{100} \right)$$

$$D_{acmod} = \$8{,}150$$

6. Use Equation 11 to calculate the expected annual damages between T_{cmod} and T_{cmax}:

Equation 11. Calculating expected annual damages for an event of severe damage in a Level 1 analysis.

$$D_{acmax} = \frac{D_{cmod} + D_{cmax}}{2} * \left(\frac{1}{T_{cmod}} - \frac{1}{T_{cmax}} \right)$$

For the example,

$$D_{acmax} = \frac{1{,}630{,}000 + 3{,}227{,}000}{2} * \left(\frac{1}{100} - \frac{1}{500} \right)$$

$$D_{acmax} = \$19{,}428$$

7. Use Equation 12 to calculate the total annualized damages, which is the sum of D_{acmod} and D_{acmax}:

Equation 12. Calculating total annualized damages for a Level 1 analysis.

$$D_{ac} = D_{acmond} + D_{acmax}$$

For the example,

$$D_{ac} = \$8{,}150 + \$19{,}428 = \$27{,}578$$

8. Find the present value coefficient for the remaining project useful life (i.e., the remaining service life during the period of projected climate change) from Appendix B. For this example, the project useful life is 50 years and assumes the OMB A-94 rate of 7 percent. So, for this example:

$$PVC = 13.801$$

9. Calculate the present value of total expected damages under current conditions using Equation 13:

Equation 13. Calculating the present value of total expected damages under current conditions.

$$D_{Tc} = D_{ac} * PVC$$

For this example,

$$D_{Tc} = \$27{,}578 * 13.801 = \$380{,}604$$

D_{Tc} is also equal to the value of a hazard mitigation or resilience project that would eliminate all damages for even the 500-year return interval discharge in the absence of climate change. A hazard mitigation or resilience measure costing more than this would not be cost-effective if discharges (and hence damages) do not increase in the future.

10. Associate discharges with each of the three return periods T_{cnd}, T_{cmod}, and T_{cmax} under current (no climate change) conditions. This step will provide Q_{cnd}, Q_{cmod}, and Q_{cmax}. For this example, assume:

$$Q_{cnd} = 9{,}000 \text{ cfs}$$
$$Q_{cmod} = 10{,}505 \text{ cfs}$$
$$Q_{cmax} = 13{,}982 \text{ cfs}$$

Table 15 summarizes this example for current climate conditions:

11. Create a graph by plotting the return periods T_{cnd}, T_{cmod}, and T_{cmax} on a logarithmic scale on the *x*-axis against the associated discharges on the *y*-axis. This can be done manually using logarithmic graph paper or on a computer using a spreadsheet program with graphing capabilities. The graph creates a straight-line trend showing return periods and expected discharges. For this example, the graph is shown in Figure 22.
12. Create a second graph by plotting the discharges on the *x*-axis (with a "normal" as opposed to a logarithmic scale) and the estimated damages associated with each discharge on the *y*-axis. For the example, the graph is shown in Figure 23.

Establish Future Climate Conditions

1. After establishing baseline information for current climate conditions, begin to calculate future flows and associated expected damages for future climate conditions. To do this,

Table 15. Summary of flows for existing conditions for example project.

	Current Return Period, T_c	Current Damages, D_c	Current Annualized Damages, D_{ac}	Current Flow, Q_c (cfs)
T_{cnd}	50	$0	$0	9,000
T_{cmod}	100	$1,630,000	$8,150	10,505
T_{cmax}	500	$3,227,000	$19,428	13,982
Total annualized damages			$27,578	

start by identifying the climate change scenario or level of risk to be used for analysis (see Chapter 3 in this guidebook and Chapters 4–6 in HEC-17). For this example, a Gumbel distribution was applied to data from EPA's SWMM-CAT model (U.S. EPA, 2014), which allows users to apply monthly adjustment factors that can represent future changes in climatic conditions. SWMM-CAT uses climate models from CMIP5 and downscaled data from Climate Resilience Evaluation and Awareness Tool (CREAT) 3 for return periods of 5, 10, 15, 30, 50, 100, and 500 years. Analyses can be done for the near term (2020–2049) or far term (2045–2074) for hot/dry conditions, warm/wet conditions, or median conditions. This example assumes warm/wet conditions in the near term.

2. For the selected climate scenario, calculate the estimated future discharges for each return period T'_{fnd}, T_{fmod}, and T_{fmax}. This will result in identifying values for Q_{fnd}, Q_{fmod}, and Q_{fmax} (see Table 16).
3. Plot the future discharges under the selected climate change scenario Q_{fnd}, Q_{fmod}, and Q_{fmax} on the same graph as the baseline conditions. For this example, SWMM-CAT discharge outputs for climate-adjusted scenarios under near-term, warm/wet conditions are summarized in Figure 24.
4. Extend the linear trend for future climate conditions to the same discharge value for T_{fnd} (in this example, 9,000 cfs). This provides an estimate of the climate-adjusted return period

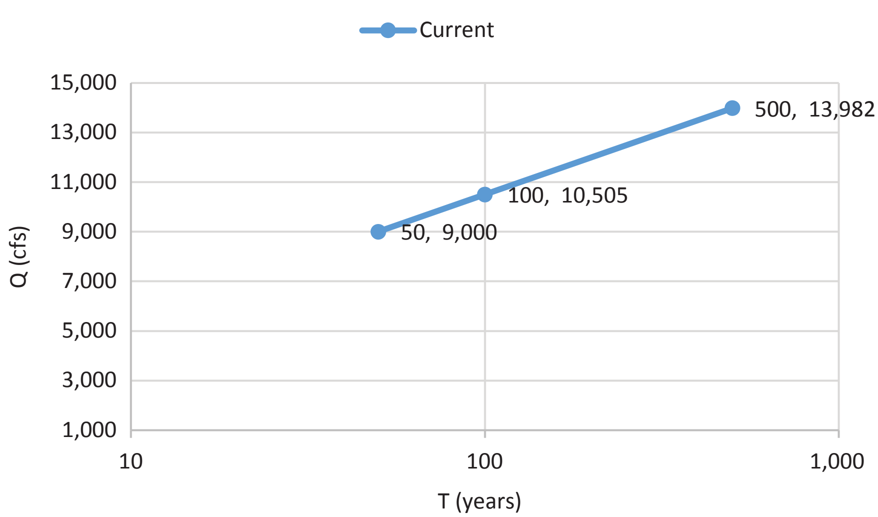


Figure 22. Logarithmic graph of return periods and associated flows under existing conditions for example project.

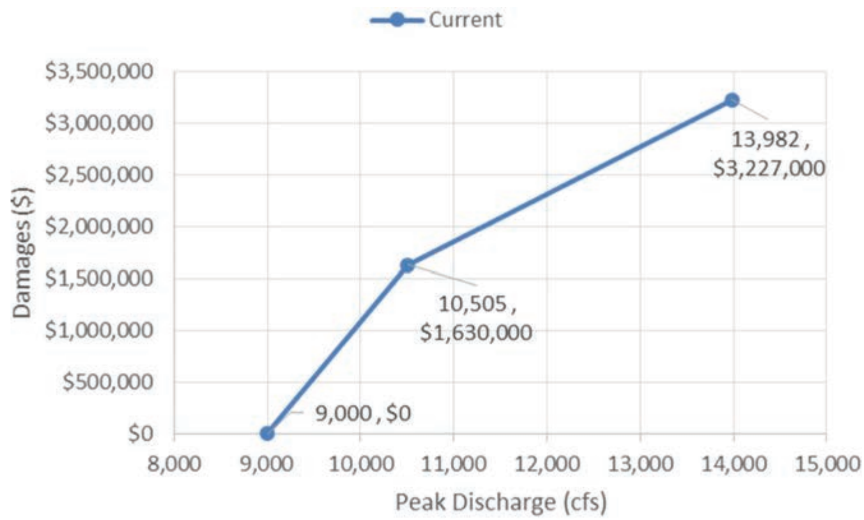


Figure 23. Peak discharge and associated damages under current conditions for example project.

Table 16. Estimated flows under future climate conditions for example project.

	Future Return Period, T_f	Future Flow, Q_f (cfs)
T'_{fnd}	50	9,979
T_{fmod}	100	11,665
T_{fmax}	500	15,562

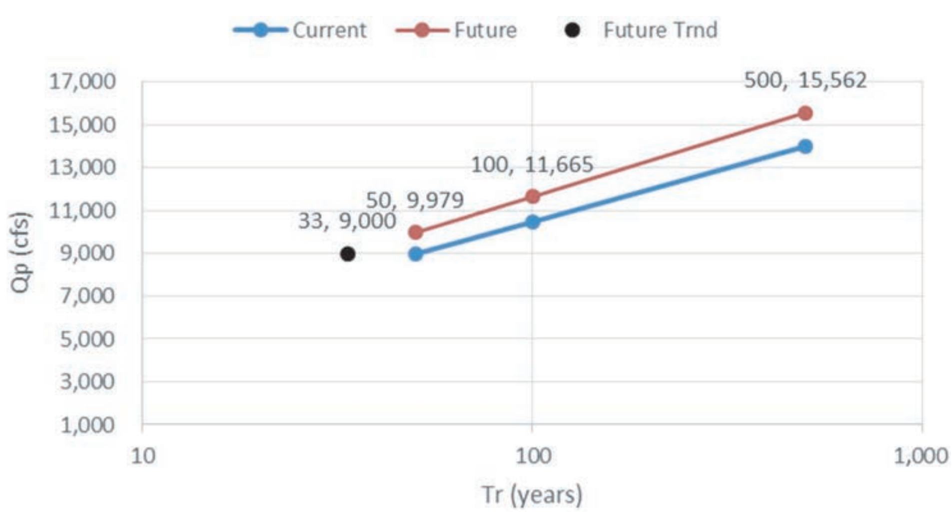


Figure 24. Estimated return periods and associated flows for current and future climate conditions for example project.

for the base flow (in this example, approximately 33 years). Alternatively, the future return period for the selected climate scenario can be calculated using Equation 14 and Equation 15:

Equation 14. Calculating the logarithmic value of the climate-adjusted return period for the base flow under future conditions.

$$LogT_{fnd} = logT_{fmod} - (LogT_{fmod} - LogT_{fnd}) * \frac{Q_{fmod} - Q_{cnd}}{Q_{fmod} - Q_{fnd}}$$

and

Equation 15. Calculating the value of the climate-adjusted return period for base flow under future conditions.

$$T_f = 10^{LogTf}$$

Using these equations for this example,

$$Log\ T_{fnd} = \log(100) - (Log\ 100 - Log\ 50) * \frac{11{,}665 - 9{,}000}{11{,}665 - 9{,}979}$$

$$Log\ T_{fnd} = 1.524$$

$$T_{fnd} = 10^{1.524} = 33.4 \text{ years for } Q = 9{,}000 \text{ cfs}$$

5. Set the future damages corresponding to T_{fnd} to D_{fnd} = \$0, as this value corresponds to the same discharge Q_{fnd} (i.e., $Q_{cnd} = Q_{fnd}$). Interpolate the damages linearly for each of the revised future discharges using Equation 16, Equation 17, and Equation 18 such that

Equation 16. Interpolating damages for future discharges for little damage.

$$D'_{fnd} = D_{cnd} + \frac{(Q_{fnd} - Q_{cnd})}{(Q_{cmod} - Q_{cnd})} * (D_{cmod} - D_{cnd})$$

and

Equation 17. Interpolating damages for future discharges for moderate damage.

$$D_{fmod} = D_{cmod} + \frac{(Q_{fmod} - Q_{cmod})}{(Q_{cmax} - Q_{cmod})} * (D_{cmax} - D_{cmod})$$

and

Equation 18. Interpolating damages for future discharges for severe damage.

$$D_{fmax} = D_{cmax} + \frac{(Q_{fmax} - Q_{cmax})}{Q_{cmax}} * D_{cmax}$$

For the example:

$$D'_{fnd} = 0 + \frac{(9{,}979 - 9{,}000)}{(10{,}505 - 9{,}000)} * (1{,}630{,}000 - 0) = 1{,}060{,}312$$

$$D_{fmod} = 1{,}630{,}000 + \frac{(11{,}665 - 10{,}505)}{(13{,}982 - 10{,}505)} * (3{,}227{,}000 - 1{,}630{,}000) = 2{,}162{,}793$$

$$D_{fmax} = 3{,}227{,}000 + \frac{(15{,}562 - 13{,}982)}{13{,}982} * 3{,}227{,}000 = 3{,}591{,}659$$

Plotting the damages against the peak discharges yields a curve for climate-adjusted flows shown in Figure 25.

Figure 25. Interpolated damages for peak flows under future climate conditions for example project.

6. Calculate the annualized damages with climate adjustment using a similar approach to Equation 10, substituting the climate-adjusted values for the current condition values. For the example:

$$D'_{afnd} = \frac{(\$0 + \$1,060,312)}{2} * \left(\frac{1}{33.4} - \frac{1}{50}\right) = \$5,270$$

$$D_{afmod} = \frac{(\$1,060,312 + \$2,162,793)}{2} * \left(\frac{1}{50} - \frac{1}{100}\right) = \$16,116$$

$$D_{afmax} = \frac{(\$2,162,793 + \$3,591,659)}{2} * \left(\frac{1}{100} - \frac{1}{500}\right) = \$23,018$$

$$D_{af} = \$5,270 + \$16,116 + \$23,018 = \$44,404$$

$$D_{Tf} = \$44,404 * 13.801 = \$612,820$$

7. Table 17 summarizes the climate-adjusted values for the example.
8. Use Equation 19 to compare the additional damages for the base case with and without climate adjustment:

Equation 19. Calculating the additional damages for the base case with and without climate adjustment (i.e., value of cost-effective adaptation measures).

$$\Delta D_T = D_{Tf} - D_{Tc}$$

$$\Delta D_T = \$612,820 - \$380,604 = \$232,216$$

Table 17. Summary of flows and damages for future climate conditions.

	T	Q (cfs)	D	D_a
T_{fnd}	33	9,000	$0	$0
T'_{fnd}	50	9,979	$1,060,312	$5,270
T_{fmod}	100	11,665	$2,162,793	$16,116
T_{fmax}	500	15,562	$3,591,659	$23,018

Table 18. Comparison of Level 1 analysis results using 7 percent and 3 percent discount rates.

	7% Discount Rate	3% Discount Rate
Present Value Interest Factor	13.801	25.730
PV of Project Benefits (current climate conditions)	$380,604	$709,582
PV of Future Damages (future climate conditions)	$612,820	$1,142,082
PV of Acceptable Project Cost (differential)	$232,216	$432,500

This value represents the additional present value of the expected damages from climate change during the remaining bridge useful life. A hazard mitigation or resilience measure aimed at maintaining the current frequency-damage structure (design level) while accounting for climate change must cost less than this value to be cost-effective. For this example, such a measure could increase the safe capacity of the hydraulic structure from 9,000 cfs to at least 9,979 cfs and increase the cost over the base case by no more than $232,216. Based on engineering cost estimates (Chapter 4), enlarging the culvert or installing multiple culverts might be cost-effective, while installing a box or arch culvert might not be cost-effective.

In addition to performing the analysis using the OMB-recommended 7 percent discount rate for the Level 1 analysis detailed on the previous pages, a sensitivity analysis was performed for the same example using a 3 percent discount rate in accordance with OMB guidance to reflect greater uncertainty associated with future climate risk. Using a 3 percent discount rate for the Level 1 analysis example on the previous pages changes the present value coefficient from 13.801 to 25.730, yielding benefits of $1,142,082 (versus $612,820 for a 7 percent discount rate). Future damages for the base case are calculated as $709,582 (i.e., $27,578 * 25.730 using Equation 13), which increases the acceptable project cost differential over the base case to $432,500 (i.e., $1,142,082 – $709,582) (Table 18). Under these conditions, the box or arch culvert might also be cost-effective.

The sensitivity analysis shows the impacts that uncertainty associated with climate risk can have on acceptable project costs. Practitioners will need to follow current federal guidance on which discount rate to use in analysis when federal funds are used in project funding; however, these individuals will need to determine what discount rate is acceptable and reflects expected risk when funding sources other than federal funds are being used for projects.

Case Study

As part of FHWA's climate vulnerabilities pilot studies, the Minnesota DOT (MnDOT, 2014) evaluated the threat of flash flooding to the state's highway system (https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/minnesota/final_report/index.cfm). Asset types within the system identified as being susceptible to flash flooding included bridges, large culverts, pipes, and roads paralleling streams. MnDOT developed a series of metrics for each asset to evaluate its vulnerability, which allowed MnDOT to score each asset and rank vulnerability according to scores. For the study, two facilities were chosen for further evaluation. Both were large culverts. This case study applies a Study Level 1 analysis to one of the culverts, Culvert 5648, which carries MN-61 over Silver Creek in the Arrowhead region northeast of Two Harbors (Figure 26).

Culvert 5648 has two cells, each with a 10-foot span (width) by 10-foot rise (height) and a length of about 90 feet (Figure 27). The culvert was built in 1963 and is at the end of its useful life. It is anticipated that precipitation levels will increase over the life of any new facility installed at this location.

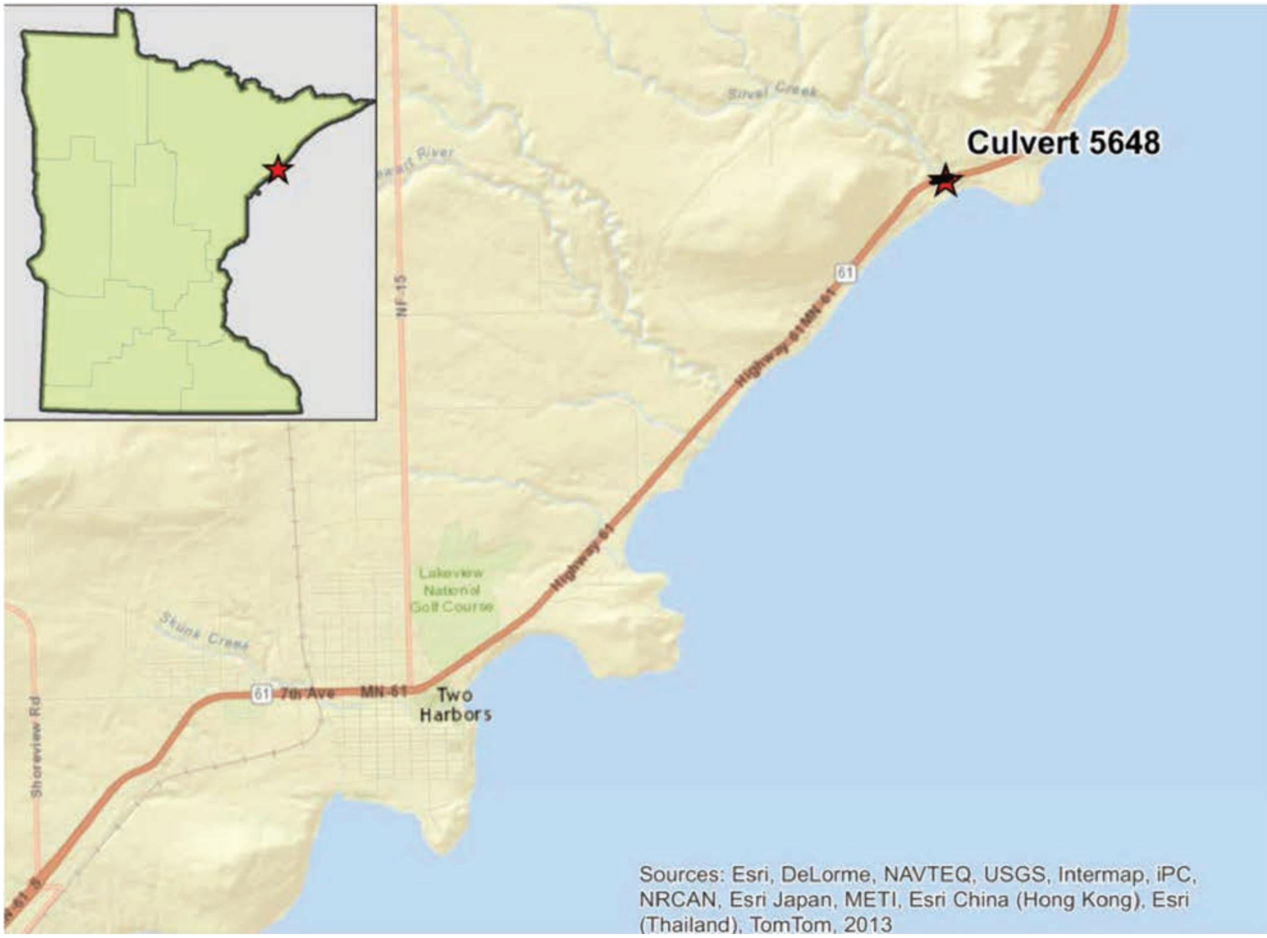


Figure 26. MnDOT evaluated Culvert 5648 for cost-effective adaptations to climate change (MnDOT, 2014).

Figure 27. Upstream side of Culvert 5648 (MnDOT, 2014).

MnDOT used a software tool called SimCLIM to evaluate future projections for three precipitation scenarios: RCP 4.5, RCP 6.0, and RCP 8.5. All three scenarios considered 24-hour precipitation depths. Storm events with return periods of 2, 5, 10, 25, 50, 100, and 500 years were analyzed. Projections were obtained for three time periods through the year 2100, which coincides with the anticipated end of useful life of the new facility.

MnDOT used the U.S. Department of Agriculture Natural Resources Conservation Service's WinTR-20 program to model peak flows through the culvert for the various storm events analyzed. Hydrologic analyses included assumptions for future land cover based on a build-out of current zoning.

A HEC-RAS model was used to evaluate the performance of the culvert under current and future peak flows. MnDOT made assumptions regarding the design of a base case and three potential climate-resilient alternatives:

- **Base case.** Replace the existing culvert in-kind; include upgrades for required freeboard (3 feet) for 50-year flood stage and fish passage per regulatory requirements. Estimated cost: $710,000.
- **Option 1.** Replace the existing culvert with a two-cell culvert having a 16-foot span (width) and 14-foot rise (height). This assumes the culvert will be sunk 2 feet into the stream bed to facilitate fish passage. This option is optimized for the low climate scenario in 2100. Estimated cost: $770,000.
- **Option 2.** Replace the existing culvert with a 52-foot simple span bridge. This approach is optimized to meet the medium climate scenario in 2100. Estimated project cost: $1,130,000.
- **Option 3.** Replace the existing culvert with a 57-foot simple span bridge. This approach is optimized for the high climate scenario in 2100. Estimated project cost: $1,210,000.

Depth-headwater elevation curves with and without social costs were developed for each option. The software model COAST was used to evaluate the cost-effectiveness of each option using a 2 percent discount rate. The results indicated that, if social costs are included in the analysis, Option 1 is the most cost-effective approach for all three climate scenarios. If social costs are excluded from the analysis, replacement-in-kind is the most cost-effective approach for the low rainfall scenario, while Option 1 is the most cost-effective for the moderate and high rainfall scenarios.

A Study Level 1 analysis was conducted using the data with social costs for the moderate scenario for a project useful life extending to 2100. The projected peak flows are summarized in Table 19.

Table 19. Summary of discharges for Culvert 5648 for the medium scenario for 2100.

24-Hour Storm Return Period (years)	Existing Discharges (cfs)	Medium Scenario Discharges for 2100 (cfs)
2	770	1,230
5	1,350	2,000
10	1,880	2,660
25	2,690	3,670
50	3,370	4,500
100	4,140	5,420
500	6,090	7,800

Depth-damage data and a depth-damage curve were provided for Option 1. Because no data were available for the base case, the Option 1 data were applied to base conditions as well. Table 20 presents the depth-damage data for Option 1.

The depth-damage data were correlated with the discharge-elevation curve (Figure 28) and projected peak flows (Table 21) to associate flows with different levels of damages, as shown in Table 22.

The data were used to conduct a Study Level 1 analysis. Initial values used are shown in Table 23 and Table 24.

The expected annual damages were calculated using Equation 10 through Equation 12. The annualized damages were calculated as

$$D_{acnd} = \$0$$

$$D_{acmod} = \$570$$

$$D_{acmax} = \$1,712$$

$$D_{ac} = \$570 + \$1,712 = \$2,282$$

Total damages over the project useful life were calculated as

$$D_{Tc} = \$2,282 * 39.745 = \$90,698$$

Table 20. Depth-damage data for Culvert 5648.

Flood Elevation (ft)	Physical Damage and Repair Cost	Socioeconomic Costs			Property	Total Cost	Damage (%)	Notes
		Detour		Injury				
		Days in Effect	Cost					
605	$0	0	$0	$0	$0	$0	0%	
614	$0	0	$0	$0	$0	$0	0%	
615	$30,000	0	$0	$0	$0	$30,000	8%	Embank-ment erosion starts
616	$30,000	0	$0	$0	$0	$30,000	8%	
617	$40,000	0	$0	$0	$0	$40,000	10%	
618	$50,000	0	$0	$0	$0	$50,000	13%	
619	$70,000	0	$0	$0	$0	$70,000	18%	
620	$80,000	0	$0	$0	$0	$80,000	20%	
621	$100,000	0	$0	$0	$0	$100,000	25%	
622	$130,000	0	$0	$0	$0	$130,000	33%	
623	$160,000	0	$0	$0	$0	$160,000	40%	
624	$200,000	0	$0	$0	$0	$200,000	50%	
625	$250,000	1	$140,000	$0	$0	$390,000	98%	Overtop-ping
626	$320,000	5	$700,000	$80,000	$0	$1,100,000	275%	
627	$400,000	15	$2,100,000	$80,000	$0	$2,580,000	645%	

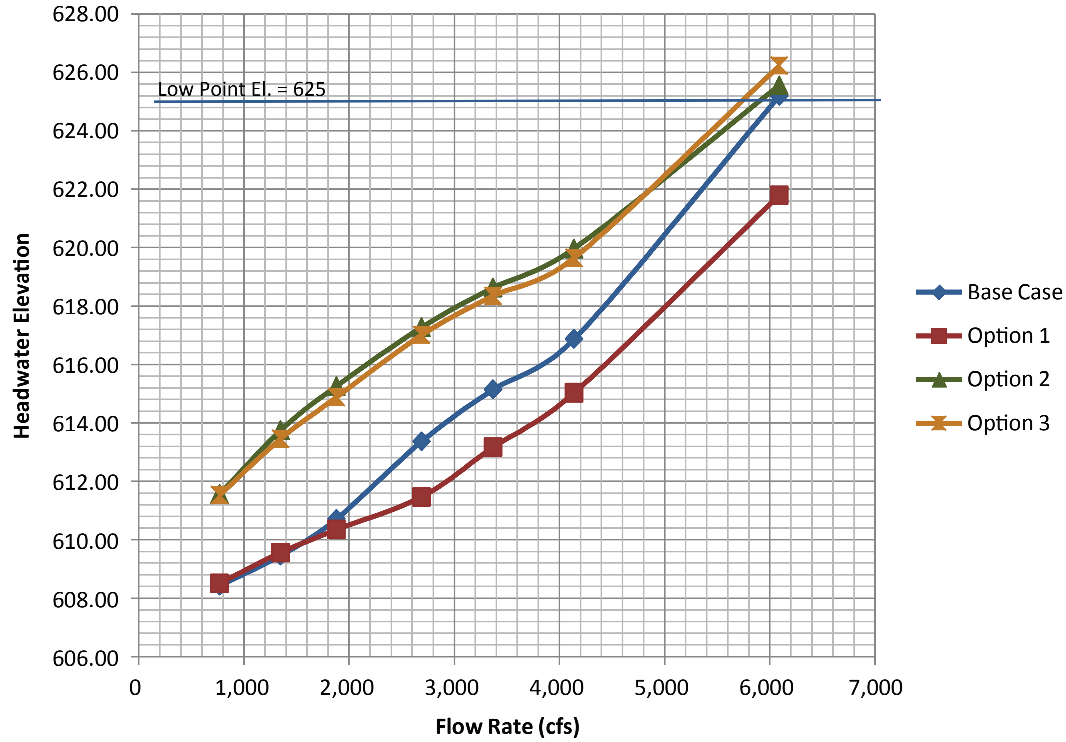


Figure 28. Depth-flow curves for Culvert 5648 replacement options (MnDOT, 2014).

Table 21. Expected flows for various return periods and climate scenarios for Culvert 5648.

24-Hour Storm Return Period	Existing Dis-charges (cfs)	Low Scenario Discharges			Medium Scenario Discharges			High Scenario Discharges		
		2040 (cfs)	2070 (cfs)	2100 (cfs)	2040 (cfs)	2070 (cfs)	2100 (cfs)	2040 (cfs)	2070 (cfs)	2100 (cfs)
2-year storm	770	1,070	1,100	1,120	1,090	1,160	1,230	1,180	1,370	1,550
5-year storm	1,350	1,760	1,810	1,830	1,800	1,900	2,000	1,930	2,190	2,460
10-year storm	1,880	2,360	2,420	2,450	2,420	2,540	2,660	2,580	2,920	3,250
25-year storm	2,690	3,260	3,350	3,390	3,340	3,500	3,670	3,550	4,010	4,460
50-year storm	3,370	4,010	4,120	4,170	4,113	4,300	4,500	4,360	4,920	5,480
100-year storm	4,140	4,810	4,940	5,000	4,930	5,170	5,420	5,240	5,940	6,610
500-year storm	6,090	6,870	7,060	7,150	7,040	7,410	7,800	7,520	8,590	9,630

Table 22. Summary of discharges and expected damages for Culvert 5648 under medium climate scenario conditions.

24-Hour Storm Return Period	Existing Discharges (cfs)	Elevation (estimated) (ft)	Estimated Damages (Base Case)	Medium Scenario Discharges 2100 (cfs)	Elevation	Estimated Damages (Option 1)
2-year storm	770	608.5	$0	1,230	608.6	$0
5-year storm	1,350	609.5	$0	2,000	609.6	$0
10-year storm	1,880	610.4	$0	2,660	611.4	$0
25-year storm	2,690	613.5	$0	3,670	613.2	$0
50-year storm	3,370	615.1	$30,000	4,500	615	$30,000
100-year storm	4,140	616.8	$38,000	5,420	619.6	$76,000
500-year storm	6,090	625	$390,000	7,800	627	$2,580,000

Table 23. Initial data used to conduct a Level 1 analysis for Culvert 5648.

	Return Period, T_c (years)	Current Flow, Q_c (cfs)	Estimated Damages ($)
T_{cnd}	25	2,690	$0
T_{cmod}	100	4,140	$38,000
T_{cmax}	500	6,090	$390,000

Table 24. Additional data used for a Study Level 1 analysis of Culvert 5648.

Project useful life (years)	80
Interest rate (%)	2%
Present value coefficient	39.745

This means that the in-kind replacement culvert is expected to sustain damages totaling $90,698 over its useful life of 80 years under current climate conditions.

Next the analysis was adjusted to account for climate change. As stated in Table 23, it was assumed that the $0 damage condition would still apply for a design flow of 2,690 cfs, but a new recurrence interval needed to be calculated for this damage-flow combination to incorporate the impacts of climate change. Using Equation 14 and Equation 15, the climate-adjusted recurrence interval was calculated to be 12 years. This same process was used to find the climate-adjusted recurrence intervals for the future flows in the medium scenario to 2100. Table 25 shows the recurrence intervals calculated.

The annualized damages were calculated for this data based on Equation 10 and Equation 12. They were found to be

$$D'_{afnd} = \$704$$

$$D_{afint1} = \$423$$

$$D_{afmod} = \$1,502$$

$$D_{afint2} = \$953$$

$$D_{afmax} = \$6,470$$

$$D_{af} = \$704 + \$423 + \$1,502 + \$953 + \$6,470 = \$10,052$$

Table 25. Interpolated values calculated for Study Level 1 analysis of Culvert 5648.

	Return Period, T_c (years)	Current Flow, Q_c (cfs)	Estimated Damages ($)
T_{fnd}	12	2,690	$0
T'_{fnd}	25	3,670	$30,000
T_{fint1}	36	4,140	$38,000
T_{fmod}	100	5,420	$133,000
T_{fint2}	157	6,090	$390,000
T_{fmax}	500	7,800	$2,580,000

Multiplying $10,052 by the present value coefficient of 39.745 results in total damages of $399,517. So, the expected damages over the life of an in-kind replacement culvert under the medium scenario climate change conditions will be approximately $399,517. The difference in damages to the in-kind replacement of the culvert with and without climate change considerations is equal to $308,780.

$$\$399{,}517 - \$90{,}697 = \$308{,}820$$

This means that a climate adaptation project that costs less than the cost of the in-kind replacement plus $308,820 would likely be cost-effective. In this case, the cost of the in-kind replacement project is $710,000, so a project costing $1,018,820 would be cost-effective. Reviewing the costs of the options considered by MnDOT, Option 1 is likely to be cost-effective, while Options 2 and 3 are not. These findings are consistent with the analyses completed by MnDOT.

Application of Study Level 1 Analysis to Sea Level Rise

The same approach used to complete a Study Level 1 analysis for riverine flooding conditions can also be applied to SLR with minor modifications. Instead of using discharges (Qs), flood elevations including wave height (in feet) are associated with recurrence intervals and levels of damage. Sea level rise calculators can be used to estimate future flood elevations. Even though the relationship between frequency and flood elevation changes with time, the relationship between frequency and damage remains somewhat constant (see Figure 21).

To summarize the steps in the approach to completing a Study Level 1 analysis for SLR, establish baseline conditions then establish future (sea level rise) conditions.

Establish Baseline Conditions

1. Identify the largest return period for which there will be no damages, likely the design return period. Identify the flood elevation associated with this recurrence interval. Set these equal to Tide El_{cnd} and T_{cnd}.
2. Identify a return period associated with an event that would cause moderate damages. This will be T_{cmod}. The corresponding flood elevation will be Tide El_{cmod}.
3. Identify a return period for which damages would be practically maximized. This maximum, realistically occurring return period is T_{cmax}. The corresponding flood elevation will be Tide El_{cmax}.
4. Estimate total damages associated with T_{cmod} and T_{cmax}. These will be D_{cmod} and D_{cmax}.
5. Use Equation 10 to calculate the expected annual damages between T_{cnd} and T_{cmod}.
6. Use Equation 11 to calculate the expected annual damages between T_{cmod} and T_{cmax}.
7. Use Equation 12 to calculate the total annualized damages, which is the sum of D_{acmod} and D_{acmax}.
8. Find the present value coefficient for the remaining project useful life (i.e., remaining service life during the period of projected climate change) from Appendix B.
9. Use Equation 13 to calculate the present value of total expected damages under current conditions.

Establish Future (Sea Level Rise) Conditions

10. Use a sea level rise calculator (or other model) and find the NOAA gauge closest to the location of interest.

11. For the selected gauge and project useful life duration, find the adjusted return period under SLR conditions for the flood elevations used to establish current conditions (i.e., Tide El_{cnd}, Tide El_{cmod}, and Tide El_{cmax}). To get a smoother curve, identify one more point, Tide El'_{fnd}, between Tide El_{fnd} and Tide El_{fmod} and the associated flood recurrence interval that includes SLR.
12. Associate levels of damages with the SLR-adjusted return periods. As stated previously, the level of damages associated with a given elevation is likely to remain essentially the same, so D_{fmod} and D_{fmax} will remain the same for Tide El_{fmod} and Tide El_{fmax}; only the recurrence intervals have changed. Use the SLR calculator to determine the recurrence interval associated with the additional point chosen in Step 11. Interpolate damages associated with this flood elevation and return using a modified version of Equation 16:

$$D'_{fnd} = D_{cnd} + \frac{(Tide\ El'_{find} - Tide\ El_{cnd})}{(Tide\ El_{fmod} - Tide\ El_{fnd})} * (D_{fmod} - D_{fnd})$$

13. Calculate the annualized damages with SLR using a similar approach to Equation 10, substituting the SLR-adjusted values for the current condition values.
14. Use Equation 12 to calculate the total annualized damages for SLR conditions.
15. Find the present value coefficient for the remaining project useful life (i.e., remaining service life during the period of projected climate change) from Appendix B.
16. Use Equation 13 to calculate the present value of total expected damages under SLR conditions.

Example Study Level 1 Analysis with Sea Level Rise

This example is fictitious and used only for illustration purposes.

The City of Galveston wishes to incorporate enhancements into its transit system to reduce damages and service disruptions from future storm events. It also wants to account for SLR in its adaptation planning process.

The enhancements will be designed for the current 500-year flood and will have a project useful life of 50 years. Galveston's transit system currently has an average daily ridership of 5,000 people. The initial project cost is $250,000, and annual O&M costs associated with the project will be $5,000. The improvements will not result in any system-user delays; however, without implementing the project, system users will experience additional one-way trips that are 10 miles longer and take an additional half hour. The delays are estimated to last for 7 days until the system becomes fully operational again. This will affect 200 bus trips per day.

Using the FTA recurrence interval adjustment calculator for SLR, recurrence intervals have been found for a project useful life of 50 years and equivalent flood elevations including wave height and SLR based on the NOAA gauge for Galveston Pier 21 (Table 26).

Table 27 summarizes the SLR-adjusted recurrence intervals obtained from the RI calculator for recorded flood elevations.

Table 26. Estimated flood recurrence intervals including sea level rise at Galveston Pier 21.

Flood Elevation Including Wave Height (ft)	Recurrence Interval without SLR (years)	Estimated Equivalent Recurrence Interval with SLR (years)
10.12	50	18.35
13.00	100	29.82
17.76	500	145.69

Table 27. Estimated equivalent recurrence intervals incorporating sea level rise for recorded floods near Galveston Pier 21.

Flood Elevation Including Wave Height (ft)	Recurrence Interval without SLR (years)	Estimated Equivalent Recurrence Interval with SLR (years)
6.50	2.60	1.79
8.90	17.45	8.83
11.34	90.90	29.32

The 50-, 100-, and 500-year recurrence interval information for current conditions was used to reflect current pre-resilience conditions. These recurrence intervals were selected because the adaptation/resilience project is intended to protect against the current 500-year event. Next, the sea level rise–adjusted recurrence intervals were used for the same tide elevations to calculate the pre-resilience future (sea level rise) conditions. In addition, one tide elevation in between the current 50- and 100-year events was used for interpolation purposes. The data inputs and results are summarized in Table 28.

The results of the analysis suggest that a project costing more than about $173,500 will not be cost-effective.

Table 28. Study Level 1 analysis results for sea level rise adaptation example near Galveston, Texas.

		Current Pre-Resilience Conditions				Future (Sea Level Rise) Pre-Resilience			
						T_f (Year)	Tide El (ft)	Interpolated Damages, D_f	Base Case Future Annualized Damages, D_{af}
		Tide El (ft)	Damages (in Current $)	Annualized Damages, D_{ac}	T_c (Year)	18.35	10.12	$0	$0
Max return period resulting in no damages	T_{cnd}	10.12	$0	$0	50.00	29.32	11.34	*$42,361*	$432
Next level return period resulting in some damages	T_{cmod}	13.00	$100,000	$500	100.00	29.82	13.00	*$100,000*	$41
Return period resulting in maximum damages	T_{cmax}	17.76	$1,250,000	$5,400	500.00	145.69	17.76	*$1,250,000*	$18,003
	Total Annualized Current Damages			$5,900		Total Annualized Future Damages			$18,475
Project Useful Life	PUL	50				Future Damages for Base Case			**$254,972**
Discount Rate (%)	i	7				Current Damages for Base Case			**$81,424**
Present Value Coefficient	PVC	13.801				Additional Damages for Base Case			**$173,548**
Present Value of Benefits	**Benefits**	**$81,424**				Max. Acceptable Project Cost			**$173,548**

CHAPTER 8

Study Level 2 Climate Resilience Cost-Benefit Analysis

Introduction to Study Level 2 Analysis

A Study Level 2 analysis builds on a Study Level 1 analysis. A Study Level 2 analysis uses existing conditions without climate change only to calculate the new return period for future conditions with climate change, that is, the maximum return period under climate change conditions for which no damages will occur, T_f. A Study Level 2 analysis then calculates future damages with and without hazard mitigation or resilience measures in place. Methodologies, data sources, and analysis tools for doing so are found in Appendix J, Appendix K, and Appendix L.

Process Walk-Through with an Example

Select Data Inputs and Data Sources

The data inputs and sources for a Level 2 analysis are the same as those used for a Level 1 analysis, plus the estimated future flows or design capacity for the adaptation options and estimated damages for future events after adaptation is incorporated.

Parameter	Value Used in Scenario	Data Source(s)
Facility of concern	Culvert	Project file
Geographic location of the facility/corridor under consideration	Chesterfield, Virginia	Site plan, maps
Hazard(s) of concern	Flood	Hazard analysis
Current design criteria—flow rate	9,000 cfs	Engineering designs and plans
Current design criteria—recurrence interval	50-year event	AASHTO design manual, U.S. DOT design manual
Discount rate(s) to be used in the analysis	7%	OMB A-94
Expected useful life of current facility	Within 2 years	Capital plan, O&M records
Expected useful life of replacement facility	50	Virginia DOT design guides
Anticipated time frame for implementation of adaptation strategies	Less than 2 years	Capital plan

Parameter	Value Used in Scenario	Data Source(s)
Scenario(s) to be used for analysis	Precipitation conditions in 2049	NOAA Atlas 14, SWMM-CAT for warmer, wetter conditions 2045–2075
Design concepts of adaptation strategies	Enlarge culvert, add multiple culverts, use box or arch culvert	Engineering Department
Cost estimate for each adaptation strategy (life-cycle costs, including any long-term adverse impacts from the adaptation strategy)	Cost estimates	Historical data, recent bids for similar work, cost-estimating software
Identification of any non-quantifiable costs associated with the project	None	U.S. DOT analysis
Estimates of damages sustained from the hazard of concern	Loss estimates	Historical data, engineering analyses, O&M records, depth-damage curves
Estimates of additional benefits resulting from the project, separated by physical/social/environmental if using multiple discount rates	Benefits estimates	FEMA benefit-cost analysis tools for drought, ecosystem services, and post-wildfire mitigation
Identification of any non-quantifiable benefits associated with the project	None	U.S. DOT analysis
Estimated future flows for adaptation options	Future 50-, 100-, and 500-year events	Level 1 analysis
Estimated damages for future events after adaptation is incorporated	Future 50-, 100-, and 500-year events	Level 1 analysis

Complete Level 1 Analysis

The same numerical example used in Chapter 7 will be used to illustrate a Study Level 2 analysis. A Study Level 2 analysis begins by using the same data and calculations as in a Level 1 analysis. A worksheet for this Level 2 analysis is included in Appendix H. Table 29 summarizes the results from the example Study Level 1 analysis from Chapter 7.

Figure 23 in Chapter 7 makes apparent that the curve developed using only three points has limited accuracy, as damages associated with a discharge under current conditions can exceed damages for the same discharge under climate-adjusted conditions. Correcting for these discrepancies will enable a comparison between future conditions for the base case and future conditions that implement a hazard mitigation or resilience action.

Add Points to Curve for Future Discharges and Damages

1. Adding more points for the discharges versus return periods and damages versus discharges graphs will correct for discrepancies between existing conditions and future climate-adapted conditions. Two additional points using future return periods for current discharges should be sufficient for developing a more accurate discharge versus return period curve. Use Equation 14 from Chapter 7 to calculate climate-adapted return

Table 29. Summary of results from Study Level 1 analysis.

		Current Pre-Resilience Conditions				Future (Climate Change) Pre-Resilience			
						Q_f	T_f	Interpolated Damages, D_f	Base Case Future Annualized Damages, D_{af}
		T_c	Damages (in Current $)	Annualized Damages, D_{ac}	Q_c (cfs)	9,000	*33*	$0	$0
Max return period resulting in no damages	T_{cnd}	50	$0	$0	9,000	9,979	50	*$1,060,312*	$5,270
Return period resulting in moderate damages	T_{cmod}	100	$1,630,000	$8,150	10,505	11,665	100	*$2,162,793*	$16,116
Return period resulting in maximum damages	T_{cmax}	500	$3,227,000	$19,428	13,982	15,562	500	*$3,591,659*	$23,018
	Total Annualized Current Damages			$27,578		Total Annualized Future Damages			$44,404
Project Useful Life	PUL	50				Future Damages for Base Case			**$612,820**
Discount Rate (%)	i	7				Current Damages for Base Case			**$380,604**
Present Value Coefficient	PVC	13.801				Additional Damages for Base Case			**$232,216**
Present Value of Benefits	**Benefits**	**$380,604**				Max. Acceptable Project Cost			**$232,216**

periods for the original 100- and 500-year return periods, that is, discharges of 10,505 cfs and 13,982 cfs.

$$LogT_{fint1} = \log(T_{fmod}) - (Log(T_{fmod}) - Log(T'_{fnd})) * \frac{Q_{fmod} - Q_{cmod}}{Q_{fmod} - Q'_{fnd}}$$

$$LogT_{fint1} = \log(100) - (Log(100) - Log(50)) * \frac{11{,}665 - 10{,}505}{11{,}665 - 9{,}979} = 1.793$$

$$LogT_{fint1} = 10^{1.793} = 62 \text{ years}$$

And

$$LogT_{fint2} = \log(T_{fmax}) - (Log(T_{fmax}) - Log(T_{fmod})) * \frac{Q_{fmax} - Q_{cmax}}{Q_{fmax} - Q_{fmod}}$$

$$LogT_{fint2} = \log(500) - (Log(500) - Log(100)) * \frac{15{,}562 - 13{,}982}{15{,}562 - 11{,}665} = 2.4156$$

$$LogT_{fint2} = 10^{2.4156} = 260 \text{ years}$$

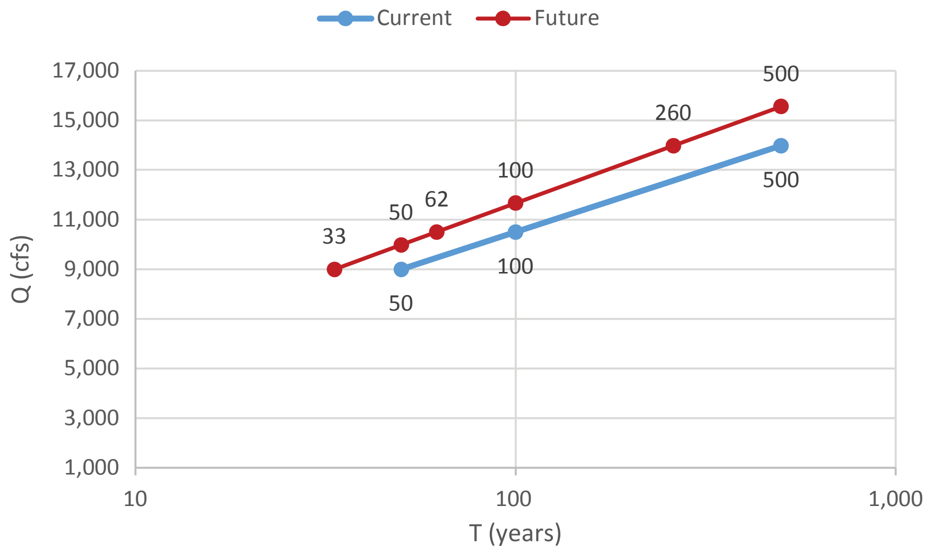


Figure 29. Estimated return periods and associated flows with additional data points for current and future climate conditions for project example.

These results mean that under assumed climate change conditions, a flow of 10,505 cfs will have a return period of 62 years, as opposed to 100 years under current conditions, and a flow of 13,982 cfs will have a return period of 260 years under assumed climate change conditions, as opposed to 500 years under current conditions.

Adding these points to the graph from the Study Level 1 analysis (Figure 21) yields the chart shown in Figure 29.

2. The damages for these newly calculated return periods of 62 and 260 years will have the same value as for the original return periods of 100 and 500 years. Damages associated with a 62-year return period under climate change conditions will be $1,630,000; damages for a 260-year return period under climate change conditions will be $3,227,000. Adding these points to the graph in Figure 23 will result in the graph shown in Figure 30.

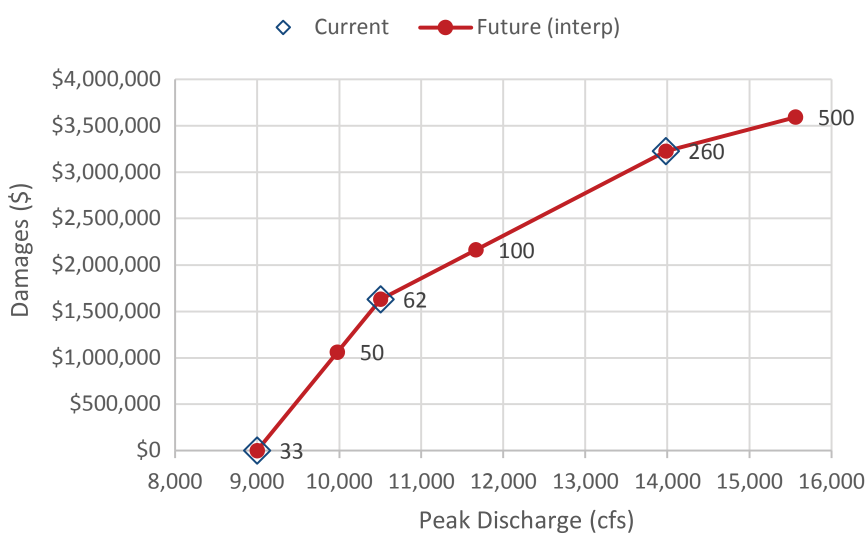


Figure 30. Smoothed curve for peak discharges and associated damages for future climate conditions for example project.

3. A Study Level 2 analysis adds the impacts that a hazard mitigation or resilience action could have on damages to the asset or corridor after the resilience action has been implemented to accommodate the modeled climate change conditions. This analysis assumes that the resilience action will eliminate future damages under climate change conditions for the future 50-year event (i.e., same as current level without climate change), and that the damages for the post-resilience future 100- and 500-year levels will be the same as the values for the current 100- and 500-year events (i.e., without climate change). Table 30 summarizes the values from the Level 1 analysis and shows the assumptions for a Study Level 2 analysis.

   It is assumed that the resilience action taken will restore the climate-adjusted conditions to mirror existing conditions. Therefore, the post-resilience values of damages for the climate-adjusted 100- and 500-year return periods are assumed to be the same as damages under current conditions, as shown in Table 30 and Table 31.
4. To determine the damages for the 62- and 260-year return periods, calculate a linear interpolation using the damage-discharge values assumed in Step 2 of this chapter.

$$D_{rint1} = 0 + \frac{(10{,}505 - 9{,}979) * (\$1{,}630{,}000 - \$0)}{(11{,}665 - 9{,}979)} = \$508{,}529$$

$$D_{rint2} = \$500{,}000 + \frac{(13{,}982 - 11{,}665) * (\$3{,}227{,}000 - \$1{,}630{,}000)}{(15{,}562 - 11{,}665)} = \$2{,}579{,}512$$

5. Calculate the annualized damages using Equation 10 from Chapter 7 (reproduced here; some differences between the spreadsheet calculations and those shown here are from rounding errors):

$$D_{arint1} = \frac{D'_{rnd} + D_{rint1}}{2} * \left(\frac{1}{T'_{rnd}} - \frac{1}{T'_{rint1}}\right)$$

$$D_{arint1} = \frac{\$0 + \$508{,}529}{2} * \left(\frac{1}{50} - \frac{1}{62}\right) = \$989$$

$$D_{armod} = \frac{\$508{,}529 + \$1{,}630{,}000}{2} * \left(\frac{1}{62} - \frac{1}{100}\right) = \$6{,}534$$

$$D_{arint2} = \frac{\$1{,}630{,}000 + \$2{,}579{,}512}{2} * \left(\frac{1}{100} - \frac{1}{260}\right) = \$12{,}964$$

$$D_{armax} = \frac{\$2{,}579{,}512 + \$3{,}227{,}000}{2} * \left(\frac{1}{260} - \frac{1}{500}\right) = \$5{,}344$$

6. Calculate the total annualized future damages for the post-resilience action by adding together all of the annualized incremental damages for the different return periods:

$$D_{ar} = \$0 + \$0 + \$989 + \$6{,}534 + \$12{,}964 + \$5{,}344 = \$25{,}831$$

7. Multiply the total annualized future damages after resilience measures have been implemented by the present value factor:

$$D_{Tr} = \$25{,}831 * 13.801 = \$356{,}494$$

8. Subtract the post-resilience total damages from the pre-resilience total damages under climate change conditions to yield the present value of the benefits associated with implementing the resilience measures:

$$Benefits = \$620{,}741 - \$356{,}494 = \$264{,}247$$

Table 30. Summary of return period calculations for Study Level 1 and Study Level 2 analyses for example climate-adapted project.

		Current Pre-Resilience Conditions				Future (Climate Change) Pre-Resilience				Future (Climate Change) Post-Resilience			
						Q_f	T_f	Interpolated Damages, D_f	Base Case Future Annualized Damages, D_{af}	Q_r	T_r	Damages, D_r (in current $)	Resilient Future Annualized Damages, D_{ar}
		T_c	Damages (in Current $)	Annualized Damages, D_{ac}	Q_c (cfs)	9,000	*33*	$0	$0	9,000	33	0	$0
Max return period resulting in no damages	T_{cnd}	50	$0	$0	9,000	9,979	50	*$1,060,312*	*$5,270*	9979	50	0	$0
Return period resulting in moderate damages	T_{cmod}	100	$1,630,000	$8,150	10,505	10,505	*62*	$1,630,000	*$5,207*	10505	62	*$0*	$0
Return period resulting in maximum damages	T_{cmax}	500	$3,227,000	$19,428	13,982	11,665	100	*$2,162,793*	*$11,623*	11665	100	$0	$0
	Total Annualized Current Damages			$27,578		13,982	*260*	$3,227,000	*$16,584*	13982	260	*$0*	$0
Project useful Life	PUL	50				15,562	500	*$3,591,659*	*$6,294*	15562	500	$0	$0
Discount Rate (%)	i	7				Total Annualized Future Damages			$44,978	Total Annualized Resilient Damages			$0
Present Value Coeff	PVC	13.801				Future Damages for Base Case			**$620,741**	Future Damages with Adaptation			**$0**
Present Value of Benefits	**Benefits**	**$380,604**				Current Damages for Base Case			**$380,604**	Future Damages without Adaptation			**$620,741**
	Mitigation Project Initial Cost			$0		Additional Damages for Base Case			**$240,137**	Adaptation Project Benefits			**$620,741**
	Annual O&M Cost of Mitigation			$0		Max. acceptable project cost to keep current conditions despite climate change			**$240,137**	Adaptation Project Cost			**$0**
	Project Total Cost			$0						Adaptation Benefit-Cost Ratio			

Table 31. The analysis assumes the climate adaptation project will return disaster damages under future climate conditions to those under current conditions.

		Current Pre-Resilience Conditions				Future (Climate Change) Pre-Resilience				Future (Climate Change) Post-Resilience			
						Q_f	T_f	Interpolated Damages, D_f	Base Case Future Annualized Damages, D_{af}	Q_r	T_r	Damages, D_r (in current $)	Resilient Future Annualized Damages, D_{ar}
		T_c	Damages (in Current $)	Annualized Damages, D_{ac}	Q_c (cfs)	9,000	*33*	$0	$0	9,000	33	0	$0
Max return period resulting in no damages	T_{cnd}	50	$0	$0	9,000	9,979	50	*$1,060,312*	*$5,270*	9979	50	0	$0
Return period resulting in moderate damages	T_{cmod}	100	$1,630,000	$8,150	10,505	10,505	*62*	$1,630,000	*$5,207*	10505	62	*$508,529*	$989
Return period resulting in maximum damages	T_{cmax}	500	$3,227,000	$19,428	13,982	11,665	100	*$2,162,793*	*$11,623*	11665	100	$1,630,000	$6,534
	Total Annualized Current Damages			$27,578		13,982	*260*	$3,227,000	*$16,584*	13982	260	*$2,579,512*	$12,964
Project useful Life	PUL	50				15,562	500	*$3,591,659*	*$6,294*	15562	500	$3,227,000	$5,344
Discount Rate (%)	i	7				Total Annualized Future Damages			$44,978	Total Annualized Resilient Damages			$25,831
Present Value Coeff	PVC	13.801				Future Damages for Base Case			**$620,741**	Future Damages with Adaptation			**$356,494**
Present Value of Benefits	**Benefits**	**$380,604**				Current Damages for Base Case			**$380,604**	Future Damages without Adaptation			**$620,741**
	Mitigation Project Initial Cost			$0		Additional Damages for Base Case			**$240,137**	Adaptation Project Benefits			**$264,248**
	Annual O&M Cost of Mitigation			$0		Max. acceptable project cost to keep current conditions despite climate change			**$240,137**	Adaptation Project Cost			**$0**
	Project Total Cost			$0						Adaptation Benefit-Cost Ratio			

Table 32. Results of sensitivity analysis for example scenario using 7 percent and 3 percent discount rates.

	7% Discount Rate	3% Discount Rate
Current Damages for Base Case	$380,604	$709,575
Future Damages for Base Case	$620,741	$1,156,516
Allowable Project Cost for No Action	$240,137	$446,940
Future Damages without Adaptation	$620,741	$1,156,516
Future Damages with Adaptation	$356,494	$664,620
Allowable Project Cost for Adaptation	$264,247	$491,896

9. For the resilience measure to be cost-effective, the NPV of the benefits minus the costs must be greater than 0. So, a resilience measure with an overall cost of less than $264,247 would be considered cost-effective.
10. Another way of evaluating the results is to use a BCR. If the ratio of the benefits to the costs is greater than 1, the measure is considered to be cost-effective. For this example, assume the cost differential between installing multiple culverts and replacing in-kind is $191,000. Then $264,247/$191,000 = 1.38, and the measure is considered cost-effective. Evaluating the BCRs for the other two options, enlarging the culvert has a BCR of $264,247/$29,000 = 9.11 and the box or arch culvert has a BCR of $264,247/$381,000 = 0.69. Based on BCRs, enlarging the culvert may be the most desirable option.

As with the Study Level 1 analysis, a sensitivity analysis was performed for Study Level 2 using a 3 percent discount rate. With the present value coefficient changing from 13.801 to 25.730, the present value of benefits associated with pre-adaptation conditions is $244,433. The results of the analysis are summarized in Table 32.

The results suggest that regardless of the interest rate used, enlarging the culvert or replacing the existing culvert with multiple culverts will be cost-effective. Replacing the existing culvert with a box or arch culvert is cost-effective only when a 3 percent discount rate is used.

Case Study

FHWA HEC-17, Section 8.4, presents a HEC-17 Level 5 analysis of a "Gulf Coast 2: Airport Boulevard Culvert" that includes a CBA of various hazard mitigation options to make the culvert resilient to increased discharges caused by future climate and land use change. The applicable design standard for this culvert is to pass a 25-year flood with no less than 2 feet of freeboard measured from the roadway edge of pavement. The option analyzed was to increase the number of culvert cells from four to six. The climate projections were custom developed by a climate scientist specifically for the project. The benefit-cost approach used in the example is complex and relies on 1,000 Monte Carlo simulations for five climate scenarios for each adaptation option. The five scenarios are

- Observed (Model Baseline) 1980–2009,
- NOAA Average Baseline,
- NOAA 90 Percent Upper Confidence Limit,
- "Wetter" Narrative 2070–2099, and
- "Drier" Narrative 2070–2099.

The comparison analysis uses the Wetter Narrative 2070–2099 scenario. The results for this scenario using the HEC-17 method indicate the present value of costs is $1.7 million

Table 33. Summary of data for Airport Boulevard Study Level 2 existing conditions CBA.

	Current Pre-Resilience Conditions				
		T_c	Damages (in current $)	Annualized Damages, D_{ac}	Q_c Observed 1980–2009 w/ Future LU (ft^3/s)
Max return period resulting in no damages	T_{cnd}	25	$0	$0	3,170
Return period resulting in moderate damages	T_{cmod}	50	$15,500,000	$155,000	4,100
Return period resulting in maximum damages	T_{cmax}	100	$17,000,000	$162,500	4,480
				$317,500	
Project Useful Life	PUL	30			
Discount Rate (%)	i	7			
Present Value Coeff	PVC	12.409			
Present Value of Benefits	Benefits	$3,939,871			

and the present value of benefits is $12.7 million, yielding an NPV of $11.0 million and a BCR of 7.3.

The data for the scenario were applied to a Study Level 2 analysis approach as described in this chapter:

- The current condition discharges used in the Study Level 2 analysis were taken from Table 8.3 in HEC-17 for Observed 1980–2009 conditions (see Table 33).
- The future discharges were taken from HEC-17, Table 3, for the Wetter Narrative 2070–2090 projection (see Table 34).
- The current expected damages calculated for each return period were not available from HEC-17 and so were calculated to be consistent with the information provided in the HEC-17 case study.
- Damages for future conditions were capped at the current damages under the 100-year discharge conditions.

Table 34. Summary of future conditions for Airport Boulevard Level 2 CBA.

		Future (Climate Change) Pre-Resilience			
		Q_f "Wetter" Narrative w/ Future LU 2070–2099 (ft3/s)	T_f	Interpolated Damages, D_f	Base Case Future Annualized Damages, D_{af}
	T_{fnd}	3,170		$0	$0
Max return period resulting in no damages	T'_{fnd}	4,100		$15,500,000	
Return period resulting in moderate damages	T_{fmod}	4,480		$17,000,000	
Return period resulting in maximum damages	T_{fmax}	5,710	25	$17,000,000	
		7,050	50	$17,000,000	
		7,840	100	$17,000,000	

- Unlike HEC-17, which used 1,000 Monte Carlo simulations, the following Study Level 2 analysis used just one fixed scenario.
- Based on the information for adaptation Option 1 (i.e., increasing four cells to six), the safe capacity of the culverts will increase from 3,170 cfs to 4,450 cfs. This information was used to estimate the post-adaptation damages, and damages for higher return periods were capped at the maximum pre-adaptation future conditions level.

Table 33 shows the data used for the comparative Study Level 2 analysis.

1. To begin the analysis, calculate annualized damages (i.e., damage increment) for current conditions:

$$D_{acmod} = \frac{D_{cnd} + D_{cmod}}{2} * \left(\frac{1}{T_{cnd}} - \frac{1}{T_{cmod}}\right)$$

$$D_{acmod} = \frac{\$0 + \$15{,}500{,}000}{2} * \left(\frac{1}{25} - \frac{1}{50}\right) = \$155{,}000$$

$$D_{acmax} = \frac{D_{cmod} + D_{cmax}}{2} * \left(\frac{1}{T_{cmod}} - \frac{1}{T_{cmax}}\right)$$

$$D_{acmax} = \frac{\$15{,}500{,}000 + \$17{,}000{,}000}{2} * \left(\frac{1}{50} - \frac{1}{100}\right) = \$162{,}500$$

$$D_{ac} = \$155{,}000 + \$162{,}500 = \$317{,}5000$$

2. Apply the present value coefficient to calculate the present value of total damages over the life of the culvert for current conditions (and hence the minimum benefits needed):

$$D_{Tc} = \$317{,}500 * 12.409 = \$3{,}939{,}871$$

3. Assign discharges for future climate change conditions, as shown in Table 34 and Figure 31. Discharges for the "Wetter" narrative scenario were obtained from HEC-17, Table 8.3, for the 25-, 50-, and 100-year storms.

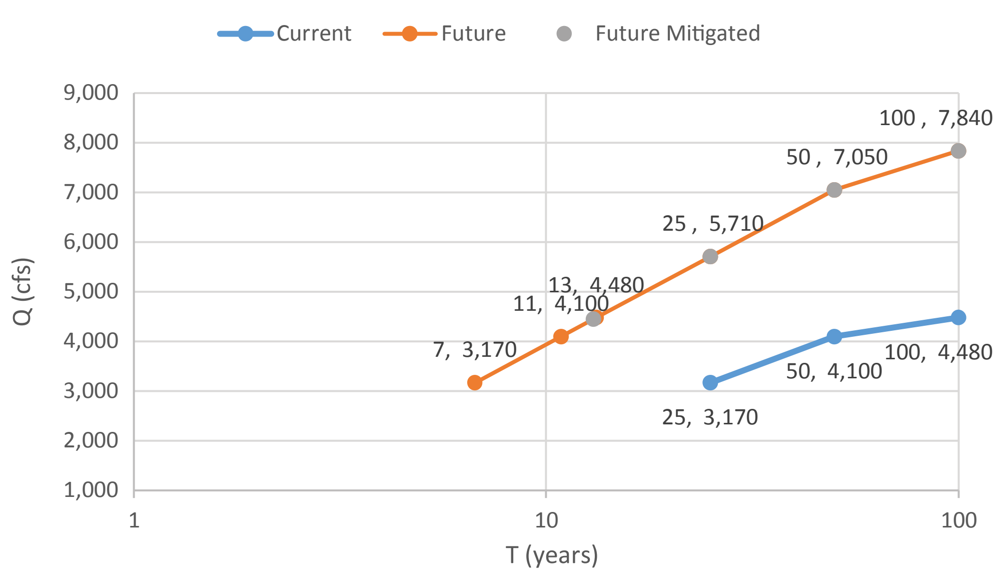


Figure 31. Summary of return periods and associated flows for current and future conditions for Airport Boulevard Study Level 2 CBA.

4. Calculate the adjusted return periods for the future conditions (“Wetter” narrative) before implementing the Option 1 adaptation strategy:

$$LogT_{fint1} = \log(50) - (Log(50) - Log(25)) * \frac{7{,}050 - 4{,}480}{7{,}050 - 5{,}710} = 1.122$$

$$T_{fint1} = 10^{1.122} = 13.2 \text{ years}$$

$$LogT'_{fnd} = \log(25) - (Log(25) - Log(13.2)) * \frac{5{,}710 - 4{,}100}{5{,}710 - 4{,}480} = 1.035$$

$$T'_{fnd} = 10^{1.035} = 10.9 \text{ years}$$

$$LogT_{fnd} = \log(13.2) - (Log(13.2) - Log(10.9)) * \frac{4{,}480 - 3{,}170}{4{,}480 - 4{,}100} = 0.83$$

$$T_{fnd} = 10^{0.83} = 6.8 \text{ years}$$

5. Interpolate the damage increments based on the calculated return periods:

$$D'_{afnd} = \frac{\$0 + \$15{,}500{,}000}{2} * \left(\frac{1}{6.8} - \frac{1}{10.9}\right) = \$428{,}697$$

$$D_{afint1} = \frac{\$15{,}500{,}000 + \$17{,}000{,}000}{2} * \left(\frac{1}{10.9} - \frac{1}{13.2}\right) = \$259{,}756$$

$$D_{afmod} = \frac{\$17{,}700{,}000 + \$17{,}000{,}000}{2} * \left(\frac{1}{13.2} - \frac{1}{25}\right) = \$607{,}879$$

$$D_{afint2} = \frac{\$17{,}700{,}000 + \$17{,}000{,}000}{2} * \left(\frac{1}{25} - \frac{1}{50}\right) = \$340{,}000$$

$$D_{afmax} = \frac{\$17{,}700{,}000 + \$17{,}000{,}000}{2} * \left(\frac{1}{50} - \frac{1}{100}\right) = \$170{,}000$$

$$D_{af} = \$428{,}697 + \$259{,}756 + \$607{,}879 + \$340{,}000 + \$170{,}000 = \$1{,}806{,}332$$

$$D_{Tf} = \$1{,}806{,}332 * 12.409 = \$22{,}414{,}774$$

$$\Delta D_T = \$22{,}414{,}774 - \$3{,}939{,}871 = \$18{,}474{,}903$$

Table 35 and Figure 32 summarize the information calculated thus far for pre-adaptation damages.

6. According to HEC-17, the proposed Option 1 will increase the safe capacity of the culverts from 3,170 cfs to 4,450 cfs. This flow is assumed to reasonably have the same recurrence interval of 13.2 years as the 4,480 cfs flow. Again, maximum damages were capped at the maximum damages for existing conditions, and damages occurring after Option 1 is implemented for future climate conditions were calculated:

$$D_{rmod} = \$15{,}500{,}000 + ((5{,}710 - (4{,}450 - 3{,}170)) - 4{,}100) * \frac{\$17{,}000{,}000 - \$15{,}500{,}000}{4{,}480 - 4{,}100}$$

$$D_{rmod} = \$16{,}802{,}632$$

Table 36 and Figure 33 summarize damages calculated for after-adaptation conditions.

Table 35. Updated summary of annualized damages for pre-adaptation future conditions for Airport Boulevard Study Level 2 CBA.

		Future (Climate Change) Pre-Resilience			
		Q_f "Wetter" Narrative w/ Future LU 2070–2099 (ft3/s)	T_f	Interpolated Damages, D_f	Base Case Future Annualized Damages, D_{af}
	T_{fnd}	3,170	**7**	$0	$0
Max return period resulting in no damages	T'_{fnd}	4,100	**11**	$15,500,000	**$440,446**
Return period resulting in moderate damages	T_{fmod}	4,480	**13**	$17,000,000	**$266,759**
Return period resulting in maximum damages	T_{fmax}	5,710	25	$17,000,000	**$604,776**
		7,050	50	$17,000,000	**$340,000**
		7,840	100	$17,000,000	**$170,000**

7. Calculate the future mitigated damage increments and find the total value of future damages after adaptation measures are implemented for future climate conditions:

$$D_{armod} = \frac{\$0 + \$16,684,211}{2} * \left(\frac{1}{13.2} - \frac{1}{25}\right) = \$298,293$$

$$D_{arint2} = \frac{\$16,684,211 + \$17,000,000}{2} * \left(\frac{1}{25} - \frac{1}{50}\right) = \$336,842$$

$$D_{armax} = \frac{\$17,700,000 + \$17,000,000}{2} * \left(\frac{1}{50} - \frac{1}{100}\right) = \$170,000$$

$$D_{ar} = \$298,293 + \$336,842 + \$170,000 = \$805,135$$

$$D_{Tr} = \$805,135 * 12.409 = \$9,990,920$$

$$\Delta D_T = \$22,414,774 - \$9,990,920 = \$12,423,854$$

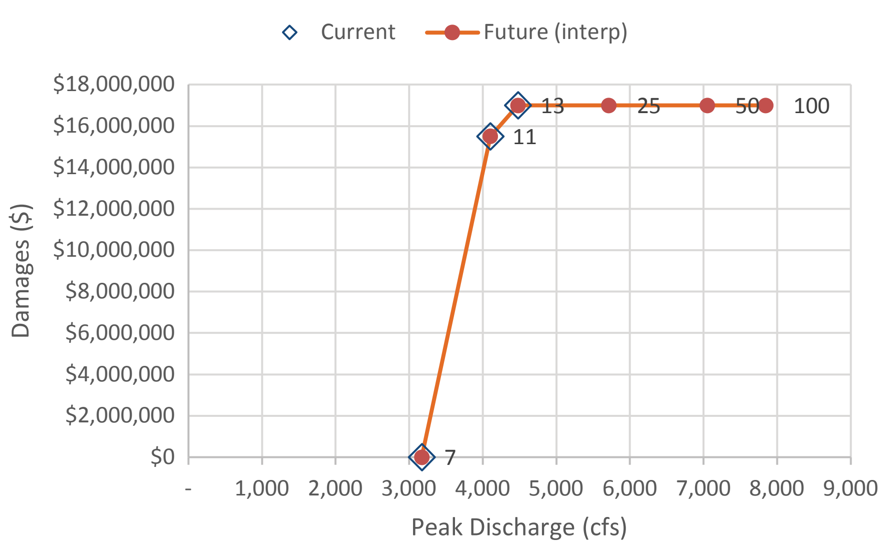


Figure 32. Peak discharges and associated damages for pre-adaptation future conditions for Airport Boulevard Study Level 2 CBA.

Table 36. Summary of damages for future conditions after adaptation measures are implemented for Airport Boulevard Study Level 2 CBA.

		Future (Climate Change) Pre-Resilience				Future Post-Resilience Option 1			
		Q_f "Wetter" Narrative w/Future LU 2070–2099 (ft3/s)	T_f	Inter-polated Damages, D_f	Base Case Future Annualized Damages, D_{af}	Q_r	T_r	Damages, D_r (in current $0)	Resilient Future Annualized Damages, D_{ar}
	T_{fnd}	3,170	**7**	$0	$0	4,480	13	0	$0
Max return period resulting in no damages	T'_{fnd}	4,100	**11**	$15,500,000	**$440,446**	5,710	25	**$16,684,211**	
Return period resulting in mod-erate damages	T_{fmod}	4,480	**13**	$17,000,000	**$266,759**	7,050	50	**$17,000,000**	
Return period resulting in max-imum damages	T_{fmax}	5,710	25	$17,000,000	**$604,776**	7,840	100	**$17,000,000**	
		7,050	50	$17,000,000	**$340,000**				
		7,840	100	$17,000,000	**$170,000**				

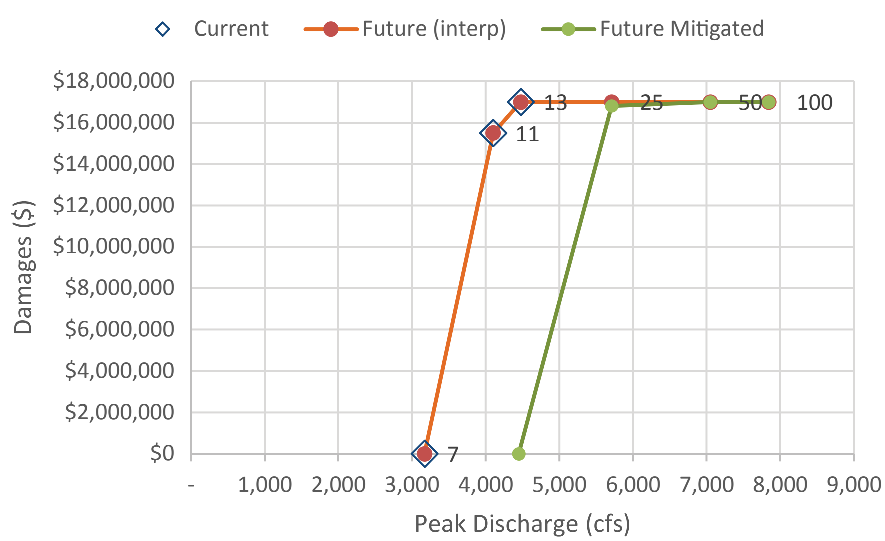


Figure 33. Peak discharges and associated damages after adaptation measures are implemented for Airport Boulevard Study Level 2 CBA.

Table 37. Summary of results comparing a HEC-17 Monte Carlo simulation CBA approach with Study Level 2 analysis results for Airport Boulevard CBA.

	HEC-17 Monte Carlo approach	Level 2 Analysis (rounding)	Level 2 Analysis (spreadsheet)
Net Present Value of Project	$11.0 million	$10,723,854	$10,936,962
BCR	7.3	7.31	7.43

So, the NPV of the benefits associated with implementing the Option 1 adaptation project is $12,423,854. The NPV of the project is equal to the difference between the benefits and the costs, which in this case were $1,700,000, so NPV of the project is $10,723,854. The BCR is $12,423,854/$1,700,000, which equals 7.31. (Calculations presented in the Level 2 analysis use rounded values for the adjusted return intervals.) Using a spreadsheet to complete the calculations (which reduces rounding errors) yields an NPV of $10,936,962 and a BCR of 7.43.

Table 37 compares the results of the Study Level 2 analysis method with the results in HEC-17.

A comparison of the analysis results indicates that the simplified Study Level 2 analysis approach provides results within 3 percent of the NPV and less than 1 percent of the BCR found using the Monte Carlo method. These results indicate that the simplified Study Level 2 analysis approach can provide accurate estimates of NPV and BCR for transportation climate adaptation projects.

Study Level 2 Analysis with Sea Level Rise

The same Galveston scenario discussed in Chapter 7 was used as the basis for completing a Study Level 2 analysis for SLR.

Additional points with recorded flood elevations between the current 50-, 100-, and 500-year tide elevations and their corresponding estimated equivalent recurrence intervals with SLR were incorporated into the analysis for future conditions without resilience/adaptation. The result was a revised estimate of $173,500 for a cost-effective adaptation project. Last, the damages associated with implementing an adaptation project that protects to the current 500-year level event was assumed, such that damages remained at $0 until the future sea level exceeded the current 500-year event, after which maximum damages were assumed to occur. The results are summarized in Table 38.

The results indicate that the proposed project has an initial cost of $250,000 and annual O&M costs of $5,000, yielding a BCR of 0.72; it is therefore not cost-effective.

Table 38. Study Level 2 analysis results for sea level rise example near Galveston, Texas.

		Current Pre-Resilience Conditions				Future (Sea Level Rise) Pre-Resilience				Future Post-Mitigation			
						T_f (Year)	Tide El (ft)	Interpolated Damages, D_f	Base Case Future Annualized Damages, D_{af}	Tr (Year)	Tide El (ft)	Interpolated Damages, D_r	Base Case Future Annualized Damages, D_{ar}
		Tide El (ft)	Damages (in Current $)	Annualized Damages, D_{ac}	T_c (Year)	18.35	10.12	$0	$0	18.35	10.12	$0	$0
Max return period resulting in no damages	Trnd	10.12	$0	$0	50.00	29.32	11.34	*$42,361*	*$432*	29.32	11.34	$0	$0
Next level return period resulting in some damages	Trnext	13.00	$100,000	$500	100.00	29.82	13.00	$100,000	*$41*	29.82	13.00	$0	$0
Return period resulting in maximum damages	Trmax	17.76	$1,250,000	$5,400	500.00	66.34	15.51	*$706,408*	*$7,443*	66.34	15.51	$0	$0
	Total Annualized Current Damages			$5,900		145.69	17.76	$1,250,000	*$8,031*	145.69	17.76	$0	$0
Project Useful Life	PUL	100				158.29	18.00	*$1,307,983*	*$699*	158.29	18.00	$1,250,000	$341
Discount Rate (%)	i	7				Total Annualized Future Damages			$16,646	Total Annualized Future Damages			$341
Present Value Coefficient	PVC	14.269				Future Damages for Base Case			**$237,523**	Future Damages for Base Case			**$4,873**
Present Value of Benefits	**Benefits**	**$84,189**				Current Damages for Base Case			**$84,189**	Current Damages for Base Case			**$237,523**
	Mitigation Project Initial Cost=			$250,000		Additional Damages for Base Case			**$153,335**	Additional Damages for Base Case			**$232,651**
	Annual O&M Cost of Mitigation=			$5,000		Max. acceptable project cost to keep current conditions despite climate change			**$153,335**	Max. acceptable project cost to keep current conditions despite climate change			**$321,346**
	Project Total Cost=			$321,346						Adaptation Benefit-Cost Ratio			**0.72**

Conclusion

Scientific studies widely show climate is beginning to exacerbate extreme weather. Higher temperatures mean more evaporation and moisture in the atmosphere and stronger storms, droughts, and heat waves. DOTs are preparing for

- Increased incidence and magnitude of extreme events common to the region;
- Unseasonal or unusual types of extreme weather hazards; and
- The gradual shifting of climate zones outside the parameters for which infrastructure was designed (Meyer et al., 2014), including
  - Higher maximum temperatures;
  - Depending on geography, wetter or drier climates;
  - Changes to expected types of winter precipitation; and
  - Rising sea level.

Such climate changes could reduce the life span of DOT assets.

For DOTs, increasingly frequent weather events present a connected set of issues with potentially serious, costly impacts on infrastructure; moreover, much of our nation's transportation infrastructure is reaching the end of its useful life. In some cases, competing priorities and limited budgets have resulted in underfunded preventive maintenance programs. In addition to extreme weather events, aging infrastructure is also being stressed by increases in population and development.

Effective planning for resilience acknowledges the multiple "1-in-100-year events" occurring in 5-, 10-, and 15-year periods, affecting DOTs around the country. Moreover, many more catastrophic events have occurred in the last decade, such as the 2013 floods in Colorado, estimated to be caused by a 1-in-1,000-year rainfall event (Minchon, 2013), and the 1-in-500-year hurricane and flood events in South Carolina in 2015 (Holmes, 2015).

In the face of changing climate and increased incidence of extreme weather, tools and policies, particularly those that address cost-effectiveness, can help DOTs make informed decisions about how to invest limited funds. In particular, CBA for climate adaptation helps provide a rigorous foundation for decision making, improving stewardship of limited public monies and transportation system resilience. CBAs can help strengthen the case for resilience investments, particularly because peak benefits usually occur later in the infrastructure life cycle (Coley, 2012). Climate resilience means recognizing that extremes are not necessarily extraordinary, and effective CBA methodologies are needed to support the ability to efficiently select between project alternatives, allowing transportation agencies to prepare, respond, and recover quickly.

CBA is not a cure-all, though. CBA has some limitations to consider when evaluating transportation projects for funding. The need to evaluate the costs and benefits associated with a project is inherent in any CBA; however, individuals compiling data for the analysis might accidentally omit certain costs or benefits. One potentially significant limitation is the ability to quantify all costs and benefits associated with a project. For example, a project could have social benefits such as improved aesthetics in a neighborhood, but the value of these visual improvements is difficult to assess. With respect to climate change, there is uncertainty associated with what conditions will be like decades into the future, and associated with this uncertainty is debate about the appropriate discount rate to use to determine the present value of future benefits. Last, the data used to conduct the analysis cannot be turned into a project budget. CBAs conducted as screening tools early in the planning process are based on conceptual designs and on costs and benefits calculated using best available information at that stage of the process. They may be useful for early budget planning but not as the basis for the final project budget.

While CBA has limitations, it is a useful tool in a DOT's planning toolbox. It can help DOTs screen projects and adaptation approaches to identify those for further consideration. As DOTs acknowledge and plan for the increased stress a changing climate and extreme weather are likely to bring, CBA can help them identify when and which adaptation measures will be considered for incorporation into a project.

APPENDIX A

Discount Rate Information

Discount Rates

The value of the discount rate can have a large impact on a long-term BCA. Lower discount rates will favor capital-intensive scenarios relative to those that have less capital up front but perhaps more ongoing costs (such as operating and maintenance, or O&M costs). As an example, a 3 percent discount rate applied to a $100 cost in 100 years is equivalent to about $5 today. At an 8 percent discount rate, in 100 years $100 would be only about $0.05 in present-day terms.

State governments generally do not have their own discount rates and defer to the federal government on the appropriate value. BCA preparers need to check to see whether the agency they are working with has a recommended discount rate to use. If none are available, the Office of Management and Budget (OMB) prepares the federal guidance.

For U.S. government analyses, OMB recommends, for a project of average risk and using public funds, using a real pre-tax 7 percent rate and a 3.1 percent rate for sensitivity analysis. If private investment alone is used as a source of capital, OMB recommends about a 10 percent discount rate. If the project will have important intergenerational benefits or costs, agencies might also consider a further sensitivity analysis using a lower but positive discount rate in addition to calculating net benefits using discount rates of 3 and 7 percent.

It is suggested to discount carbon emissions and savings using a 3 percent discount rate when using the median social cost of carbon. A 5 percent rate is suggested when using the low value of carbon (generated using a 5 percent discount rate), and 2.5 percent when using the high value.

Federal Guidance on Discount Rates

The type and value of discount rate used depends on the perspective of the organization conducting the analysis. Typically, for the type of projects discussed in this document, the organization undertaking the project is a state government, in which case a social discount rate is appropriate since the analysis is done from a broad social perspective. As a contrast, a private firm that completes a CBA will use a weighted average cost of capital that considers the cost of short-term debt, long-term borrowing, and equity weighted by the proportion of each used in the firm's capital structure.

The social discount rate can be thought of as measuring a time preference for the present over the future, and an opportunity cost that using resources today means that they are not invested for use later. The time preference can also be thought of as being composed of a pure time preference and a premium for the uncertainty that benefits and costs will materialize in future. Alternatively, the social discount rate can be thought of as measuring the opportunity for reinvestment and compounding of benefits received or costs deferred. These three effects are called, in the economics literature, the rate of time preference, the risk adjustment of the discount rate, and the social opportunity cost of capital.

For U.S. government analyses, OMB recommends using both the time preference rate (which tends to be lower and is estimated at 3 percent in real terms on a pre-tax basis) and the opportunity cost rate (which is higher and estimated at a real pre-tax 7 percent rate, reflecting the forgone rate of return).

A Possible Consensus-Based Exception to the Rule: Carbon Emissions Discounting

Practitioners of CBA for projects that include changes in CO_2 currently have some conflicting directions.

The federal administration currently mandates 7 percent (with 3 percent sensitivity) for all costs and benefits including carbon emissions and savings, whereas scientists and economists recommend a mid-point estimate of 3 percent (with a low of 2.5 percent and a high of 5 percent). Adding to the confusion is that some states are relying on carbon estimates that use the lower discount rate: "Policymakers and regulators in several states, including New York, Minnesota, Illinois and Colorado, are using the social cost of carbon to measure and reduce CO_2 impacts from their power grids" (Fairley, 2017).

In light of the conflicting federal policy and consensus recommendations, the research team suggests

- When applying to national analyses and grants, such as discretionary grant funding through the BUILD program, use a 7 percent discount rate for carbon and non-carbon costs and benefits (with a 3 percent rate as a sensitivity analysis) unless, of course, grant guidance states otherwise.
- For state analyses, follow recent (i.e., after March 2017) precedents.
- If CBA practitioners wish to follow the National Academies guidelines, which reflect the scientific and economic consensus, a 3 percent (and perhaps declining) discount rate for carbon (with 2.5 and 5 percent being high and low values) can be used. There is no guidance yet available on combining carbon and non-carbon, so the safest approach may be to present all discount rate combinations (2.5, 3, and 5 percent for carbon and 7 and 3 percent for non-carbon) and showing a range of net benefits discounted using these combinations. Before 2018, the U.S. DOT was explicit in its TIGER Cost-Benefit Guidance that all benefits and costs (that exclude carbon dioxide emissions) should be discounted at 7 percent (and 3 percent as a sensitivity analysis), and the net value of carbon dioxide emissions at the 3 percent discount rate. Regarding the lower discount rate, scientists and economists widely endorse these methodological choices. "The National Academies of Sciences and the U.S. Council of Economic Advisers strongly support a 3 percent or lower discount rate for intergenerational effects. A 7 percent rate based on private capital returns is considered inappropriate because the risk profiles of climate effects differ from private investments" (Revesz et al., 2017).

Recommendations in the report *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide* are given related to the discounting of project costs and benefits that include the social cost of carbon (National Academies of Sciences, Engineering, and Medicine, 2017). The report points out two issues related to discounting: that the rate for carbon is expected to be lower for carbon than for non-carbon net benefits because of intergenerational costs and benefits associated with climate change and that the discount rate is related to growth in the economy and hence environmental damages. Its recommendations call for the Interagency Working Group on Social Cost of Greenhouse Gases (IWG) to provide clarity on these issues. In March 2017, however, President Trump issued an executive order disbanding the IWG and rescinding its guidance documents in favor of the OMB guidance that uses a higher (7 percent) discount rate than that from the IWG (3 percent) (Presidential Executive Order, 2017).

If practitioners wish to follow the consensus view, the reason carbon costs and benefits are suggested to be discounted at a lower 3 percent discount rate than other costs and benefits (discounted at 7 percent) is that in calculating the Social Cost of Carbon (SCC), the stream of future damages is discounted to its present value in the year when the additional unit of emissions was released, using a discount rate that reflects society's marginal rate of substitution between consumption in different time periods. It does not reflect the social opportunity cost of capital.

There is a range of SCC values in the federal guidance. When using the lower (or higher) carbon numbers, earlier federal guidance said to use the 2.5 percent (or 5 percent) discount rate:

> While the SCC estimate grows over time, the future monetized value of emissions reductions in each year (the SCC in year *t* multiplied by the change in emissions in year *t*) must be discounted to the present to determine its total net present value for use in regulatory analysis. Damages from future emissions should be discounted at the same rate as that used to calculate the SCC estimates themselves to ensure internal consistency—i.e., future damages from climate change, whether they result from emissions today or emissions in a later year, should be discounted using the same rate. For example, climate damages in the year 2020 that are calculated using a SCC based on a 5 percent discount rate also should be discounted back to the analysis year using a 5 percent discount rate. (U.S. EPA, 2016a)

This is the rationale for the previous suggestion to discount carbon emissions and savings by 5 percent when using the low value (generated using a 5 percent discount rate) and, when using the high (2.5 percent) value, to discount savings by 2.5 percent.

The federal government recommends a 7 percent discount rate for carbon and non-carbon (with another calculation using a 3 percent sensitivity). The National Academies asks that the (disbanded) IWG provide clarity and guidance on a 3 percent (and perhaps declining) discount rate for carbon (with 2.5 and 5 percent being high and low values). There is no guidance on combining carbon and non-carbon, so the safest approach may be to present all discount rate combinations (2.5, 3, and 5 percent for carbon and 7 and 3 percent for non-carbon) and show a range of net benefits discounted using these combinations.

An example is shown for 10 years of (randomly generated) (real, or after inflation) carbon net benefits (benefits minus costs) between $80 and $150 and (random) real non-carbon net benefits between $800 and $2,500. The table shows the net present values (NPVs) using various discount rates.

Year	Carbon net benefits ($)	Non-carbon net benefits ($)
1	89	1,851
2	122	1,651
3	111	809
4	82	1,179
5	126	1,194
6	122	1,863
7	132	1,356
8	141	1,881
9	150	1,397
10	150	2,004

Discount Rate	NPV Carbon Net Benefits		NPV Non-Carbon Net Benefits	
2.5%	*$1,061*	A		
3.0%	$1,032	B	*$12,881*	E
5.0%	$927	C		
7.0%	**$836**	D	**$10,542**	F
Minimum	$836	G	$10,542	H
Maximum	$1,061	I	$12,881	J
Nat. Academies NPV Range	$11,469	C+F	$13,942	A+E
Overall (National Academies and Fed. Gov't) NPV Range	**$11,378**	D+F	*$13,942*	A+E

Providing a range from $11,378 to $13,942 would encompass

- The White House (and U.S. DOT) recommended NPV using a 7 percent discount rate value.
  - The low value is equal to the **bolded values** of the carbon NPV of (D) $836 plus a non-carbon NPV of (F) $10,542.
- The National Academies' highest NPV value, using 2.5 percent for carbon and 3 percent for non-carbon.
  - The high value is equal to the *italicized values* of (A) $1,061 carbon plus the non-carbon NPV of (E) $12,881.

This approach covers all the bases by providing a range of values that incorporates current federal policy and scientific and economics consensus.

Social Discount Rate

The social opportunity cost of capital is the expected rate of return forgone from other potential investments. "If government investment comes at the expense of private investment, the cost to the economy is measured by the social returns that would have been generated by that investment. This has been variously labeled the investment rate of interest, the producer rate of interest, the marginal rate of return to investment or capital, the marginal efficiency or product of capital, or the social opportunity cost of capital" (Harrison, 2010).

OMB estimates that social opportunity cost of capital, as measured by the real, pre-tax rate of return on all sources of private capital in the United States, is approximately 7 percent (OMB, 2016). This rate is the social opportunity cost of capital, the cost of diverting funds to government projects that could be productively used elsewhere. "It is the appropriate discount rate whenever the main effect of a regulation is to displace or alter the use of capital in the private sector" (OMB, 2003).

OMB also notes that if a project is expected to displace corporate business investment, sensitivity at a rate higher than 7 percent should also be analyzed, reflecting the forgone rate of return. If business investment alone is used as a source of capital, OMB puts this figure at about 10 percent. In addition, the recommended 7 percent social opportunity cost of capital only reflects the average degree of risk of displaced projects. It does not include any premium of adjustment for the uncertainty of risk for the scenarios considered.

Rate of Time Preference

> We saw why individuals might have a pure time rate of preference: People are impatient; they don't live forever; possessions can be lost, destroyed, or stolen, and opportunities disappear. A reasonable individual may discount the future for any one of these reasons—why should I pay money now to reduce damages from global warming that will only occur after I am dead?—but the same logic does not apply to society: Relative to the individuals of which they are composed, societies are immortal and uncertainties are averaged out. For this reason, there is, in fact, fairly wide consensus within the economics profession that social discount rates should indeed be lower than individual discount rates. The social discount rate is a rate of conversion of future value to present value that reflects society's collective ethical judgment, as opposed to an individualistic judgment, such as the market rate of interest. (Daly and Farley, 2004)

> When regulation primarily and directly affects private consumption (e.g., through higher consumer prices for goods and services), a lower discount rate is appropriate. The alternative most often used is sometimes called the "social rate of time preference." This simply means the rate at which "society" discounts future consumption flows to their present value. If we take the rate that the average saver uses to discount future consumption as our measure of the social rate of time preference, then the real rate of return on long-term government debt may provide a fair approximation. Over the last thirty years, this rate has averaged around 3 percent in real terms on a pre-tax basis. For example, the yield on 10-year Treasury notes has averaged 8.1 percent since 1973 while the average annual rate of change in the CPI over this period has been 5.0 percent, implying a real 10-year rate of 3.1 percent. (OMB, 2003)

So, OMB estimates the time preference rate at 3.1 percent and the social opportunity cost of capital to be 7 percent. U.S. government guidelines suggest that both be used, with a base rate of 7 percent and a sensitivity of 3.1 percent.

Social Discount Rate and Sustainability

The social discount rate is a contentious issue. For sustainability analysis in particular, there is much dissent because of the long time horizons involved. Some sustainability advocates have argued for a zero or low discount rate so that long-lived environmental costs are dealt with sooner rather than deferred for future generations. Alternatively, the benefits of distantly realized environmental improvements are not reduced in decisions made today. A zero discount rate gives equal weight to present and future generations.

> Analysts disagree whether long time horizon problems merit special consideration. Some economists and policy analysts argue that benefits accruing to future generations should not be discounted at all. Others believe that intergenerational concerns can often be addressed by using a social rate of time preference—the rate of time preference modified to reflect intergenerational equity considerations. . . . The draft EPA white paper on discounting suggests that when faced with a situation involving intergenerational concerns, the analyst should acknowledge that both sides of this debate have merit and calculate the present value of future benefit streams using both a zero discount rate (not discounting at all) and the rate of time preference (effectively discounting all expected future benefits in the same way). (U.S. EPA, 1999)

One argument for a low rate when considering sustainability issues is that the opportunity cost of capital depends on growth. Sustainability advocates point out, "the economy as a whole cannot grow indefinitely, in which case a social discount rate into the indefinite future may be inappropriate" (Daly and Farley, 2004).

The profitability of investments used in the opportunity cost calculation is "'profitable' because we ignore many of the costs of production. We know that all human productive activities use up natural resources and return waste to the environment, and these costs of production are often ignored" (Daly and Farley, 2004).

> Applying a zero discount rate also presumes that the estimates of very long-term consequences are as reliable as estimates of consequences that are expected in the short term. It gives equal weight to an estimated consequence in hundreds of years as it does to one that will occur today, even though there is much less reason to believe that the future consequence will unfurl as currently predicted . . . There is little doubt that people value sustainability and are concerned about the state of the environment and the quality of life that future generations will inherit. However, there are better ways to take this into account in benefit-cost analysis than by imposing a zero discount rate in the evaluation of forecast long-term consequences. (Shaffer, 2010)

OMB recommends that if a project "will have important intergenerational benefits or costs you might consider a further sensitivity analysis using a lower but positive discount rate in addition to calculating net benefits using discount rates of 3 and 7 percent" (OMB, 2003).

The Federal Emergency Management Agency (FEMA) has chosen to follow OMB's discount rate guidance. FEMA recommends that "in order to compare the future benefits to the current cost of the proposed mitigation project, a discount rate is applied over the life of the project to calculate the net present value of the expected annual benefits. For FEMA-funded mitigation projects, the discount rate is set by the Office of Management and Budget" (FEMA, 2013a).

U.S. DOT Transportation Investment Generating Economic Recovery (TIGER) Discretionary Grants guidance recommended the same (7 percent or 3 percent) discount rate, but also a 3 percent discount for monetized CO_2 emissions benefits and costs:

> [C]arbon emissions are valued differently from other benefits and costs from the perspective of discount rate. Applicants should continue to calculate discounted present values for all benefits and costs

(that exclude carbon dioxide emissions) at 7% and 3%, as recommended by OMB Circular A-94. To these non-carbon NPV benefits, the Applicant should then add the corresponding net value of carbon dioxide emissions, as calculated from the 3% SCC value. (U.S. DOT, 2016)

However, the TIGER program was discontinued in 2017 and replaced by the BUILD program in 2018. The federal grant guidance issued in 2018 recommends using the 7 percent discount rate for all analyses.

CBAs completed for grants need to follow the grant guidance. Analyses completed for other funding sources need to follow guidance issued for the funding source. If no discount rate guidance for CO_2 emissions is provided, analysts can consider conducting sensitivity analyses using both the 3 percent and 7 percent values.

International Comparisons

Social discount rate suggestions vary considerably. One review across countries identifies rate suggestions ranging from 1 percent to 15 percent (Harrison, 2010).

In small open economies, such as Canada, calculations of a weighted average social opportunity cost of capital depend on how much private investment is displaced and the ability to attract foreign investment. The lower limit on the estimate should be the cost of foreign borrowing. Federal government estimates of real pre-tax rates in Canada have fallen from 10 percent to 8 percent, but have always been higher than the U.S. 7 percent rate. In a contrary view, for the province of Ontario, Spiro (2010) estimates the social discount to be a real 5 percent rate of return.

On the SCC for cost-benefit analyses of regulatory proposals, in March 2016 Canada adopted the U.S. numbers for the SCC but converted the numbers to Canadian dollars and used the 3 percent discount rate only (rather than the 2.5 percent and 5 percent discount rates).

> Canada's interdepartmental working group recommended the adoption of the U.S. values in 2011, with a few minor adjustments. Instead of four different values, the group recommended two estimates using the same discount rate. (Environment and Climate Change Canada, 2016)

The Canadian numbers have an average and a 95th percentile both using the 3 percent social discount rate recommended by Canada's Treasury Board Secretariat Analysis Guide. The Treasury Board recommends that a real rate of 8 percent be used as the discount rate in Canada, whereas the social time preference rate, which is based on the rate at which individuals discount future consumption and projected growth rate in consumption and is a component of this discount rate, has been estimated to be around 3 percent. For the Canadian calculation of the 95th percentile estimates, the results of the one of the three models used in the U.S. estimates are not included. It was felt that one model (the FUND model) did not incorporate the low-probability, high-cost events. For reference, the FUND model gives up to a $65 value at the 95th percentile and 3 percent discount rate, whereas the PAGE model estimates up to $90 and the DICE model up to $369. By excluding the model with the lower estimates, the 95th percentile is higher in Canada than in the United States.

Social Discount Rate Conclusion

If organizations have internal recommended discount rates for evaluating projects, it is logical to use them in CBAs. Consideration may be given to the source of funds, risk of the project, and any intergenerational aspects of the project to see whether the value is appropriate. In the absence of organizational guidance or recommendations, organizations can follow the U.S. federal government guidance and use a 7 percent real discount rate.

Because of the large range of values and the potentially large impacts on the net present value of net benefits, practitioners might input the social discount rate as probability distribution in the analysis. If this approach is taken, the results reflect the difference between the time preference approach, the social opportunity cost of capital approach, and the project and cost/benefit risk-adjusted discount rate approach. Using the discount rate as an input has the added benefit that the decision can be based on one set of results for the scenarios rather than results for different discount rates. The alternative approach of doing a sensitivity analysis means that decision makers have to choose between different results based on competing economic methodologies, of which they may have little understanding.

One possible approach to using a range of discount rates would be to bound the real social discount rate at 0 percent as an extreme position (with little probability of occurring in the Monte Carlo analysis). Because the focus is on long-lived infrastructure projects that may involve intergenerational effects, based on the OMB recommendation one could use the rate of time preference of 3.1 percent as the medium value. The social opportunity cost of capital estimate of 7 percent could be used for the high end of the range.

If private funds are used, practitioners could use a private discount rate or weighted average cost of capital instead of the social cost of capital. This may be appropriate if the project proponent is a private entity. If no internal weighted average cost of capital is available, OMB recommends a 10 percent rate.

APPENDIX B

Present Value Interest Factor Table

Period (Years)	1%	3%	5%	7%	10%
1	0.9901	0.9709	0.9524	0.9346	0.9091
2	1.9704	1.9135	1.8594	1.8080	1.7355
3	2.9410	2.8286	2.7232	2.6243	2.4869
4	3.9020	3.7171	3.5460	3.3872	3.1699
5	4.8534	4.5797	4.3295	4.1002	3.7908
6	5.7955	5.4172	5.0757	4.7665	4.3553
7	6.7282	6.2303	5.7864	5.3893	4.8684
8	7.6517	7.0197	6.4632	5.9713	5.3349
9	8.5660	7.7861	7.1078	6.5152	5.7590
10	9.4713	8.5302	7.7217	7.0236	6.1446
11	10.3676	9.2526	8.3064	7.4987	6.4951
12	11.2551	9.9540	8.8633	7.9427	6.8137
13	12.1337	10.6350	9.3936	8.3577	7.1034
14	13.0037	11.2961	9.8986	8.7455	7.3667
15	13.8651	11.9379	10.3797	9.1079	7.6061
20	18.0456	14.8775	12.4622	10.5940	7.8237
25	22.0232	17.4131	14.0939	11.6536	9.0770
30	25.8077	19.6004	15.3725	12.4090	9.4269
35	29.4086	21.4872	16.3742	12.9477	9.6442
40	32.8346	23.1148	17.1591	13.3317	9.7791
45	36.0945	24.5187	17.7741	13.6055	9.8628
50	39.1961	25.7298	18.2559	13.8007	9.9148
75	52.5871	29.7018	19.4850	14.1964	9.9921
100	63.0289	31.5989	19.8479	14.2693	9.9993

APPENDIX C

Climate Information, Design Guidelines, and Data Sources

Contributors to Non-Stationarity

Climate science is still evolving, which makes planning for and incorporating climate change into adaptation projects difficult for planners and designers. One of the challenges in predicting future conditions is non-stationarity; the past can no longer be used as a basis for predicting the future. There are two primary contributors to non-stationarity—greenhouse gas emissions and land use changes.

Impacts from Emissions

The 2014 National Climate Assessment (USGCRP, 2014) reports that the majority of atmospheric warming at the global scale is attributable to human-related causes, a large portion of which are the emissions that result from burning fossil fuels (e.g., coal, oil, and natural gas). These emissions include gases capable of trapping and storing heat within the Earth's atmosphere (e.g., water vapor, CO_2, CH_4, N_2O) and particles, such as soot or black carbon, that have an overall warming effect. As part of the Earth's natural greenhouse effect, these heat-trapping gases are always present to a certain degree and, while they do not absorb short-wave energy that originates from the sun, they do absorb the long-wave energy that is re-radiated from the Earth's surface, thus ensuring that the planet remains warmer than it would be otherwise and that it is sufficiently warm to sustain life. Human-related activities have increased the concentrations of these gases and particles so that the amount of heat re-radiated to the surface has increased substantially, while less heat is allowed to escape into space, causing a gradual increase in average global surface temperatures. According to the 2014 National Climate Assessment, this effect of emissions on the Earth's heat budget is the primary cause of the global warming observed in recent decades.

Impacts from Changes in Land Use and Cover

Changes in land use and cover have also been found to have a significant effect on climate, in addition to climate-related risks to water resources. Land use refers to any human-related activity that takes place on land, which includes urbanization, agricultural activities, and deforestation. Land cover refers to the physical characteristics of the land, which are affected by land use, including vegetative cover (e.g., crops and trees) and impervious surfaces. One example of the effect of land use and cover on regional climate is the "urban heat island" effect. The high percentage of land area covered by pavement, buildings, and other types of impervious surfaces has a substantial effect on the exchange of heat and water between the ground and the atmosphere. Over the past few decades, the most significant changes in land use in the United States have been related to the amount and variety of forest cover being reduced by substantial urban development in the Northeast and Southwest, as well as to logging practices in the Southeast and Northwest.

Options for mitigating against the detrimental effects of land use and cover on climate include an expansion in the size and diversity of forests; modifications to urban development to reduce energy, transportation, and water demands (e.g., rainwater capture and reuse); and shifting agricultural practices to encourage soil carbon storage. Resistance to such practices takes into account that decisions related to land use are also affected by economic, cultural, and legal considerations. Other reasons for resistance include the difficulties inherent in the implementation of many climate-friendly modifications to current land use patterns and the fact that in the majority of cases individual land owners and their communities do not realize any direct benefits from such modifications.

Climate Models

General Circulation Models

Climate scientists have developed several quantitative models to simulate the transfer of energy and materials through the climate system (NOAA, 2017). These models allow scientists to test theories and evaluate how changes in variables could affect future conditions. General circulation models (GCMs) are mathematical models that simulate the changes in the atmosphere as a result of slow changes in some boundary conditions (such as the solar constant) or physical parameters (such as greenhouse gas concentration) (Geerts and Linacre, 1998). GCMs are developed to simulate physical processes in the atmosphere, ocean, cryosphere, and land surface, in a three-dimensional space. CMIP5 includes 39 GCMs.

GCMs generally have low resolution because of the global coverage of the models, which can make them insufficient for use for some processes that occur at a smaller scale but that can help control climate, such as topography, vegetation, and hydrology. An example of a smaller-scale phenomenon not typically captured by a GCM is a tropical cyclone (i.e., tropical depressions, tropical storms, and hurricanes); a downscaled regional climate model is typically used for this purpose (e.g., Caron, Jones, and Winger, 2011). GCMs have other sources of uncertainty in their models, such as how the various feedback mechanisms are modeled from one GCM to another. Such mechanisms include water vapor and latent warming, clouds and long-wave radiation, effects of ocean circulation, and the reflection of short-wave radiation caused by ice and snow albedo (reflectivity).

Regional Climate Models and Downscaling

So that some of the physical factors that contribute to regional and local climates, such as meteorological and earth boundary conditions that occur at smaller scales, can be taken into consideration, higher-resolution nested regional climate models (RCMs) are developed from the lower resolution GCMs or from analyses of observational data through a process known as downscaling.

Downscaling methods relate large-scale climate variables to regional and local variables. Statistical downscaling is the most common method employed and is based on the premise that regional climate is conditioned by the large-scale state of the climate and local physiographic features incapable of being resolved within the GCM. Large-scale climate variables are input into a downscaling statistical model to estimate higher-resolution local climate characteristics. Statistical downscaling methods (e.g., regressions, neural networks) are useful in regions where sufficient data exist for model calibration. Statistical downscaling can be used to be provide local information for a wide array of climate change impact applications. Disadvantages include the underlying assumption that the statistical relationships developed for the present day will hold into the future under the various possible forcing conditions. Data availability and quality are also key. Regions containing complex topography will likely have limited data available by which statistical relationships can be developed.

The other broad category of downscaling methods is dynamical downscaling. This method uses high-resolution regional simulations to dynamically extrapolate the effects of large-scale climate processes to regional or local scales of interest (NOAA, 2017). Dynamical downscaling can be done globally or at a regional level using an RCM (Evans, 2011).

Scenarios

In addition to modeling the response of the global (and regional) climate system to a change in the concentrations of greenhouse gases in the atmosphere, it is important to focus on the driving forces behind anthropogenic (human caused) climate change and on human response through technology, economics, lifestyle, and policy. Climate scenarios have been developed for these purposes. Scenarios describe potential trajectories of different aspects of the future by representing not only the processes but also the impacts and potential responses related to anthropogenic climate change. Scenarios are used to transfer information from one research area to another (e.g., emissions to climate modeling) and to explore the implication of climate change on policy and decision making. It is important to note that the objective in the development of various scenarios is not to provide a method by which to predict the future, but to better understand uncertainty in various alternative futures under a changing climate and to determine how robust various decisions will be under a range of possible futures. In other words, scenarios were not developed to predict what is going to occur in the future; instead, they facilitate obtaining results from climate models and determining the effects of various decisions under a wide range of potential future conditions.

Four scenarios were developed and chosen in conjunction with the release of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2014; each considers an alternative future in global greenhouse gas and aerosol concentrations as their initial conditions in order to allow a determination of their impact on the climate system and on socioeconomic conditions. The scenarios are referred to as representative concentration pathways (RCPs) and represent the total radiative forcing pathway and level (in watts per square meter, W/m^2) that will occur in the year 2100 from cumulative human emissions of greenhouse gases from all sources. The four RCPs are RCP 8.5, RCP 6, RCP 4.5, and RCP 2.6.

- RCP 8.5 represents rising radiative forcing leading to 8.5 W/m^2 in the year 2100.
- RCP 6 and RCP 4.5 represent a stabilization in radiative forcing (without overshoot) of 6.0 and 4.5 W/m^2 after the year 2100.
- RCP 2.6 represents a peak in radiative forcing of about 3 W/m^2 before the year 2100 and declining afterwards.

RCP 8.5 considers the most pessimistic future while RCP 2.6 represents the most optimistic scenario. The use of each scenario in various climate models then gives an estimate of the range of potential future climate conditions that can be expected by the year 2100.

Several entities have developed guidance for selecting scenarios for risk-based transportation planning that consider extreme weather and climate change. These guidance documents are summarized in Table C-1.

Understanding climate risks to the transportation system is also important to determining when and how to incorporate climate adaptation into project planning. Table C-2 summarizes resources that provide guidance on understanding these risks.

Table C-1. Frameworks/guidelines for selecting scenarios for risk-based transportation planning that considers extreme weather and changing climate.

Resource Title	Author/Organization	Region
Criteria for Selecting Climate Scenarios (2013)	Intergovernmental Panel on Climate Change	International
Scenarios for Climate Assessment and Adaptation (2015)	U.S. Global Change Research Program	National
Climate Model Comparison Tool	The Infrastructure and Climate Network	Northeast
A Framework for Considering Climate Change in Transportation and Land Use Scenario Planning (2012)	The Interagency Transportation, Land Use, and Climate Change Pilot Program U.S. DOT Volpe National Transportation System Center	Pilot project on Cape Cod
Central New Mexico Climate Change Scenario Planning Project (2015)	The Interagency Transportation, Land Use, and Climate Change Pilot Program U.S. DOT Volpe National Transportation System Center	Scenario planning project—Central NM
FHWA Climate Change Vulnerability Assessment Pilot Project: Hampton Roads (2014)	FHWA Virginia Department of Transportation	Climate change vulnerability assessment model—Hampton Roads, VA

Additional Considerations

Intensity, Duration, and Frequency

When analyzing changes in precipitation patterns as part of the planning, design, and operation of a particular water resources project, the relationship between rainfall intensity, duration, and frequency, referred to as IDF curves, is important. IDF curves are a common tool used by engineers to determine the amount of rain expected to fall within a given amount of time for a desired annual exceedance probability or its reciprocal, the return period. IDF curves are often used to derive depth-duration-frequency relationships, which allow the estimation of the total rainfall amount corresponding to a return period or, conversely, the return period associated with an observed rainfall event. In order to estimate the IDF curves for a desired region, observed and computed rainfall data are required at a range of temporal resolutions. For example, durations used in NOAA Atlas 14 (https://hdsc.nws.noaa.gov/hdsc/pfds/) range from 5 minutes up to 60 days. Return periods for rainfall totals and intensities are determined using a standard rainfall distribution function (e.g., Gumbel, Log Pearson Type III, and Generalized Extreme Value, among others) and, in the case of NOAA Atlas 14, cover a range of 1 to 1,000 years. For example, if a location has a 100-year, 24-hour rainfall total of 7.43 inches, the site can expect to exceed a total of 7.43 inches of rainfall in any 24-hour period annually only once in every 100 years, which corresponds to an annual exceedance probability of 1 percent for such an event.

Gradual Change versus Extreme Events

One of the primary questions to consider when planning water resources projects in the face of a changing climate is whether to focus on the effects of gradual trends related to, for example, frequent rainfall or river discharge events, or to more drastic changes in the intensity of extreme events. To answer this question, it needs to be understood that climate change will likely

Table C-2. Sources of guidance for understanding climate risk to the transportation system.

Resource Title	Author/Organization	Links
Potential Impacts of Climate Change on U.S. Transportation (2008)	Committee on Climate Change and U.S. Transportation TRB	https://www.nap.edu/catalog/12179/potential-impacts-of-climate-change-on-us-transportation-special-report
First International Conference on Surface Transportation System Resilience to Climate Change and Extreme Weather Events (2015)	TRB	http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=4&ved=2ahUKEwjEku278sHcAhUId98KHSKiDe0QFjADegQIAxAC&url=http%3A%2F%2Fonlinepubs.trb.org%2Fonlinepubs%2Fconferences%2F2015%2FClimateChange%2FProgram.pdf&usg=AOvVaw00k-6Uv1XIWZKgMrUT34g7
National Climate Assessment, Chapter 5: Transportation (2014)	U.S. Global Change Research Program	http://nca2014.globalchange.gov/report/sectors/transportation
Building Climate Resilient Transportation (2016)	FHWA	https://www.fhwa.dot.gov/environment/climate_change/adaptation/publications/bcrt_brochure.cfm
Integrating Extreme Weather Risk into Transportation Asset Management (2012)	AASHTO	http://climatechange.transportation.org/pdf/extrweathertamwhitepaper_final.pdf
Virtual Framework for Vulnerability Assessment (2016)	FHWA	http://www.fhwa.dot.gov/environment/climate_change/adaptation/adaptation_framework/
Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation (2011)	FTA	https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_0001_-_Flooded_Bus_Barns_and_Buckled_Rails.pdf
Planning for Systems Management & Operations as Part of Climate Change Adaptation (2013)	FHWA	http://www.ops.fhwa.dot.gov/publications/fhwahop13030/
Challenges and Opportunities for Integrating Climate Adaptation Efforts across State, Regional and Local Transportation Agencies (2015)	National Center for Sustainable Transportation	https://escholarship.org/uc/item/5t88h66m
Vulnerability Assessment Scoring Tool (2015)	FHWA	https://toolkit.climate.gov/tool/vulnerability-assessment-scoring-tool-vast
Risk-Based Transportation Asset Management: Building Resilience into Transportation Assets Report 5—Managing External Threats Through Risk-Based Asset Management (2013a)	FHWA	https://www.fhwa.dot.gov/asset/pubs/hif13018.pdf

result in gradual changes in the mean of many of the variables described in the previous section. Levels at which an event is classified as extreme will also shift. The result is not that there will definitely be a higher number of extreme events but that the extreme events that will occur will be more intense compared with a scenario in which climate change does not exist. For example, the current extreme 100-year event may be classified as a less-extreme 50-year event in the future even though the intensity remains unchanged. The number of events, whether they are more or less frequent, is related to climate variability, which consists of mechanisms and global teleconnections that can cause oscillations in such variables as rainfall and discharge, resulting in certain regions being wetter or drier depending on the phase and the strength of the mechanism or teleconnections. Climate change superimposed on top of climate variability results in an exacerbation or, in some cases, a suppression of these wetter and drier conditions, causing a shift in the event magnitude associated with a specific return period. Estimating the magnitude of this shift is the focus of myriad studies related to any one of the variables already discussed and comes with much uncertainty. Any adaptive measures that are incorporated into a future climate adaptation project needs to consider both the magnitude and uncertainty of climate change impacts if any analysis of the potential benefits of such measures is to be made. Some resources for evaluating projected climate change and extreme weather impacts are summarized in Table C-3.

Table C-3. Authoritative sources of projections of future climate and sea level. The entities responsible for producing this information will provide updates over time.

Type	Source	Data	Data Publishing Date	Geographic Coverage
Atmospheric Data				
Historical Atmospheric	Expert Team on Climate Change Detection and Indices (ETCCDI)	Observation-based gridded data of extreme climate indices	2013	United States (land-only)
Historical Atmospheric	NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA)	Model reanalysis using observed historical conditions	2008–present	Global
Non-Downscaled Atmospheric and Sea Level Rise	Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5)	CMIP5*, hosted at Lawrence Livermore National Laboratory Data Portal	2013	Global
Non-Downscaled Atmospheric and Sea Level Rise	U.S. Global Change Research Program's 2014 National Climate Assessment	Predominantly SRES A2 and B1 from CMIP3	2007	United States
Downscaled Atmospheric and Hydrology	Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections	CMIP5 and CMIP3 (Western U.S. hydrology)	2007–2014	United States
Sea Level Rise Data				
Local Sea Level Rise	Global Sea Level Rise Scenarios for the United States National Climate Assessment	• Linear extrapolation of historical data (low) • IPCC AR4 (low intermediate) • Various (high intermediate and high)	2007–2012	United States

Table C-3. (Continued).

Type	Source	Data	Data Publishing Date	Geographic Coverage
Local Sea Level Rise	U.S. Army Corps of Engineers Sea Level Rise Change Curve Calculator	• Linear extrapolation of historical data (low) • Intermediate and high from IPCC and National Research Council	2015	United States
Local Sea Level Rise	NOAA's Global Sea Level Rise Scenarios for the U.S. National Climate Assessment	• Linear extrapolation of historical data (low) • Intermediate-low: considers risk primarily from expansion caused by ocean warming • Intermediate-high: same as intermediate-low with the addition of limited ice sheet loss • Highest: complete ice sheet loss	2012	United States

*CMIP data refers to the Coupled Model Intercomparison Project, a product of the IPCC. CMIP5 results correspond to the IPCC's Fifth Assessment Report and CMIP3 corresponds to the Fourth Assessment Report.

Emerging Climate Design Guidance

While currently there are no set rules for incorporating the impacts of climate change into design of infrastructure, several agencies have developed guidelines that can be considered and incorporated into the design process. These guidance documents are summarized in Table C-4.

In addition to these guidance documents, several sources of climate-related data are available that can be applied to existing models. Sources of climate data are included in Table C-5.

Some additional tools available to help estimate flooding risks from climate change are summarized in Table C-6.

Table C-4. Agencies are developing guidance regarding how to consider and incorporate climate change into the design process.

No.	Agency/ Author	Publication/ Software	Date Expiration	Summary
1	U.S. Army Corps of Engineers (USACE)	ECB-2016-25	9/16/2016 9/16/2018	**Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Design, and Projects** Engineering Construction Bulletin 2016-25 recommends that a qualitative analysis be conducted to determine observed trends reflected in gauge records, as well as consult the potential future trends projected by global climate models. For this purpose, USACE has developed a Nonstationarity Detection Tool.
2	USACE	ETL 1100-2-3	4/28/2017 4/27/2021	**Guidance for Detection of Nonstationarities in Annual Maximum Discharges** Engineering Technical Letter 1100-2-3 provides guidance for abrupt or slowly varying changes (non-stationarities) in analyses of annual maximum discharges. This guidance does not detect the potential presence of long-term persistence in the discharge time series. This ETL discusses a total of 12 non-stationarity detection statistical tests that can be applied to the annual maximum stream gauge record and is supported by a non-stationarity detection tool.
3	USACE	Nonstationarity Detection Tool	4/28/2017 4/27/2021	This ETL is supported by a web-based tool, which applies statistical tests capable of detecting abrupt non-stationarity (change points) in gauge records and allows the user to identify continuous periods of statistically homogeneous (stationary) peak stream flow records. The tool is supported by a User's Manual, but, for access, the general public is required to install a DOD Certificate. Annual maximum flow estimates of all USGS stream gauges that had over 30 years of record (as of 2014) are pre-loaded and can be accessed through the tool for each HUC-4 watershed. A total of 12 non-stationarity detection tests are available for this purpose. Subsequently, a trend analysis can be conducted on the resulting subset of stationary flow records identified using another feature of the tool.
4	USACE	Climate Hydrology Assessment tool	9/16/2016 9/16/2018	This is part of the non-stationarity detection tool. At the pour point of each HUC-4 watershed, this tool plots annual monthly maximum flows projected through 2100 by 93 different climate model simulations. Arithmetic average of the 93 projected results is also generated for each HUC-4 basin. The statistically downscaled climate model data (CMIP5) are pre-loaded in the tool.

Table C-4. (Continued).

No.	Agency/ Author	Publication/ Software	Date Expiration	Summary
5	**EPA**	Storm Water Management Model Climate Adjustment Tool (SWMM-CAT)	9/2014 N/A	SWMM-CAT is a stand-alone utility program to EPA's Storm Water Management Model (SWMM). SWMM-CAT generates location-specific adjustments for monthly evaporation, monthly rainfall, and 24-hour design rainfall depths derived using downscaled global climate model projections (CMIP3). Design rainfall adjustment factors to be applied with National Weather Service recommended values are estimated for 5-, 10-, 15-, 30, 50-, and 100-year return periods. Adjustment factors are computed for near term (2020–2049) and far term (2045–2074) for three potential future climate scenarios: hot/dry, median change, warm/wet.
6	**EPA**	Climate Resilience Evaluation and Awareness Tool Version 3.0 (CREAT)	5/2016 N/A	CREAT is a web-based informational tool to assist drinking water, wastewater, and stormwater utility owners and operators in addressing climate change risks. Access to CREAT appears to be limited to EPA employees and consultants. For projected climate conditions, CREAT uses CMIP5 projections for RCP 8.5. Total storm precipitations for future periods is one of the parameters estimated by CREAT for the purpose of estimating future threats to the water industries.
7	**FEMA**	Climate Regression Equations	3/2016	FEMA has developed climate regression equations for 21 HUC-2 watersheds covering the mainland United States to estimate 10- and 100-year peak flow discharges through 2060. These equations are unpublished.
8	**The White House**	Environmental Review and Permitting Process for Infrastructure	8/15/2017 N/A	Presidential Executive Order (EO) on Establishing Discipline and Accountability in the Environmental Review and Permitting Process for Infrastructure rescinds Executive Order 13690 establishing Federal Flood Risk Management Standards (FFRMS). FFRMS recommended three approaches to account for climate change—best available that incorporates future changes in flooding based on climate science, applying a freeboard to the 100-year flood elevation, or using 500-year flood elevation.

(continued on next page)

Table C-4. (Continued).

No.	Agency/ Author	Publication/ Software	Date Expiration	Summary
9	USGS, NY	Future Flow Explorer, Version 1.5	2015 N/A	The rural regression equations published by USGS assume climate stationarity; these equations are widely used for water resources computations. The New York State USGS has used CMIP5 projections to update the climate parameters in the 2006 regression equation. These future projections for frequency discharges are offered through a web-based application titled Application of Flood Regressions and Climate Change Scenarios. The web tool computed peak discharges for 1.25-, 1.5-, 2-, 5-, 10-, 25-, 50-, 100-, and 500-year frequency events for three time periods, 2025–2049, 2050–2074, and 2075–2099. RCP 4.5 and 8.5 simulations of five of the CMIP5 models that best reproduced the past precipitation were used in the future peak flow estimation.
10	FHWA	HEC-17	8/1/2016 N/A	HEC-17, "Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience" recommends methodologies to evaluate the stationarity or non-stationarity of past climate at a location of interest by examining rainfall and stream flow records. If a trend is detected, HEC-17 proposes methodologies to account for that change in design parameters (rainfall and discharge).
11	North-east Regional Climate Center	New York–Specific Intensity-Duration-Frequency (IDF) Curves	2015	Intensity-duration-frequency (IDF) curves published for New York consider two emissions scenarios (RCP 4.5 and RCP 8.5) and cover three time periods: through 2039, 2040–2069, and 2070–2099. IDFs for 2-, 5-, 10-, 25-, 50-, and 100-year return periods are considered.

Table C-5. Sources of climate data.

Data Type	Source	URL
Coastal levels (observed)	NOAA Tides and Currents	https://tidesandcurrents.noaa.gov/products.html
Drought indices (satellite)	NOAA NCEI	https://www1.ncdc.noaa.gov/pub/data/cirs/climdiv/
Drought indices (satellite)	NOAA CPC	http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/palmer_drought/
Elevation (satellite)	USGS EE	https://earthexplorer.usgs.gov/
Evaporation (observed)	NOAA NCEI	https://www.ncdc.noaa.gov/cdo-web/datasets
Evaporation (observed)	NOAA NCEI	http://climate.ncsu.edu/cronos
Evaporation (satellite)	NASA MODIS	https://modis.gsfc.nasa.gov/data/dataprod/index.php
Groundwater levels (observed)	USGS NWIS	http://waterdata.usgs.gov/nc/nwis/current/?type=flow
Groundwater levels (observed)	NC DWR	http://www.ncwater.org/?page=343
Land cover (satellite)	NC DWR	https://earthexplorer.usgs.gov/
Land cover (satellite)	MRLC NLCD	https://www.mrlc.gov/
Precipitation index	NOAA NCEI	https://www.ncdc.noaa.gov/temp-and-precip/drought/nadm/indices
Rain (observed)	NOAA NCEI	https://www.ncdc.noaa.gov/cdo-web/datasets
Rain (observed)	NC CRONOS	https://climate.ncsu.edu/cronos
Rain (radar)	NOAA NCEI	https://www.ncdc.noaa.gov/nexradinv/index.jsp
Rain (satellite)	NOAA NCEI	https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00979
Rain (satellite)	NOAA NCEI	https://www.ncei.noaa.gov/data/precipitation-persiann/access/
Rain (satellite)	NASA GPM	https://pps.gsfc.nasa.gov/ppsindex.html
Rain (satellite)	NASA MODIS	https://modis.gsfc.nasa.gov/data/dataprod/index.php
Reservoir inflow/levels (observed)	USACE	http://epec.saw.usace.army.mil/
Reservoir inflow/levels (observed)	Duke Energy	https://www.duke-energy.com/community/lakes
Sea level trends (observed)	NOAA	https://tidesandcurrents.noaa.gov/sltrends/sltrends.html
Snow/ice (observed)	NOAA	https://www.ncdc.noaa.gov/snow-and-ice/daily-snow/
Snow/ice (satellite)	NASA MODIS	https://modis.gsfc.nasa.gov/data/dataprod/index.php
Soil characteristics (observed)	USDA	https://sdmdataaccess.nrcs.usda.gov/
Soil moisture (observed)	NOAA CPC	http://www.cpc.ncep.noaa.gov/products/Soilmst_Monitoring/US/Soilmst/Soilmst.shtml
Soil moisture (observed)	NC CRONOS	http://climate.ncsu.edu/cronos
Soil moisture (satellite)	NASA MODIS	https://modis.gsfc.nasa.gov/data/dataprod/index.php
Streamflow (observed)	USGS NWIS	http://waterdata.usgs.gov/nc/nwis/current/?type=flow
Surface water levels (observed)	USGS NWIS	http://waterdata.usgs.gov/nc/nwis/current/?type=flow

(continued on next page)

Table C-5. (Continued).

Data Type	Source	URL
Temperature (observed)	NOAA NCEI	https://www.ncdc.noaa.gov/cdo-web/datasets
Temperature (observed)	NC CRONOS	http://www.nc-climate.ncsu.edu/cronos
Vegetative health (satellite)	USGS EE	http://earthexplorer.usgs.gov
Vegetative health (satellite)	NASA NEO	http://neo.sci.gsfc.nasa.gov
Vegetative health (satellite)	USGS LP DAAC	https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table
Wind speed/direction (observed)	NOAA NCEI	https://www.ncdc.noaa.gov/cdo-web/datasets
Wind speed/direction (observed)	NC CRONOS	http://www.nc-climate.ncsu.edu/cronos

Table C-6. Tools available to help estimate risks from climate change on flooding.

Tool	Description	URL
SimCLIM	SimCLIM is a software tool designed to facilitate the assessment of risks from climate change. It uses CMPI5 climate data and presents results in map, graph, and chart formats.	http://www.climsystems.com/simclim/
SWMM-CAT	EPA's Storm Water Management Model (SWMM) is used to plan, analyze, and design for stormwater runoff, combined sanitary sewers, and drainage systems in urban areas. The CAT add-on allows climate change projections to be incorporated into the SWMM analysis. SWMM-CAT provides a set of location-specific adjustments that were derived from CMIP data.	https://www.epa.gov/water-research/storm-water-management-model-swmm#add-in
SLAMM: Sea Level Affecting Marshes Model	This tool helps to illustrate the long-term impacts of sea level rise on marshes. It has been expanded to evaluate the inundation frequency of road infrastructure under future sea level rise and storm-surge conditions.	http://www.warrenpinnacle.com/prof/SLAMM/index.html
SLOSH (Sea, Lake, and Overland Surges from Hurricanes) Model	SLOSH is used as a storm-prediction model to predict storm-surge heights and wind intensity of hurricanes. It can be used to evaluate hurricane scenarios and predict storm-surge intensity.	https://slosh.nws.noaa.gov/slosh/

APPENDIX D

Cost Worksheet

	Base Case	Alternative 1	Alternative 2	Alternative 3
Pre-Construction Costs				
Design				
Permits				
Right-of-Way Acquisition				
Displacement/Relocation				
Other				
SUBTOTAL				
Construction Costs				
Land acquisition				
Construction (labor, materials, equipment)				
General Conditions				
Overhead and Profit				
Contingency				
Project Management				
User Cost - Delays during construction				
User Cost - Detours during construction				
Other				
SUBTOTAL				
Operations and Maintenance (from LCCA or other)				
Disposal				
Environmental Costs				
Habitat Loss				
Wetlands Loss				
Other				
SUBTOTAL				
Social Costs				
Increased ambient noise				
Loss of recreational use				
Other				
SUBTOTAL				
TOTAL*				

*TOTAL is the sum of the SUBTOTALs plus Operations and Maintenance plus Disposal.

APPENDIX E

Cost-Estimating Tools

In general, most DOTs have developed in-house cost databases and cost-estimating software or spreadsheets to reflect conditions and practices in their geographic region; however, a few guides and tools have been developed that are intended to be more universal.

Tools

AASHTO Practical Guide to Cost Estimating. Provides practical guidance that serves those charged with the development of DOT cost estimates and with managing the estimating process.

AASHTO Technical Committee on Cost Estimating. Provides a focal point and working group to review, develop, and recommend AASHTO's positions on cost estimating and risk-based estimating for transportation projects.

NCHRP Report 625: Procedures Guide for Right-of-Way Cost Estimation and Cost Management. Builds on *NCHRP Report 574* to provide a more in-depth analysis of the problems and practices of right-of-way cost estimating and cost management.

U.S. Government Accountability Office Cost Estimating and Assessment Guide. Establishes a consistent methodology that is based on best practices and that can be used across the federal government for developing, managing, and evaluating capital program cost estimates. It provides principles to guide assessment of the credibility of a program's cost estimate for budget and decision-making purposes and the program's status using earned value management (EVM).

Major Project Program Cost Estimating Guidance. FHWA provides guidance for preparation of a total program cost estimate for a major project.

Cost and Oversight of Major Highway and Bridge Projects: Issues and Options. GAO identifies ways to enhance federal oversight of transportation projects that use federal funds, including improving cost performance of major projects and improving the quality of initial cost estimates.

NCHRP Report 688: Determining Highway Maintenance Costs. Presents a practical, robust, and flexible process for determining an agency's full costs associated with performing highway maintenance.

NCHRP Project 20-07(152), "Project Cost Estimating: A Synthesis of Highway Practice." Provides a synthesis of state DOT project cost-estimating experience and presents information on effective ways to structure cost-estimating methodologies (link not available).

NCHRP Project 20-07(274), "Price Indexing in Transportation Construction Contracts." Describes the current state of DOT practice in using price indexing or cost escalation clauses in construction contracts, and provides information for DOT staff making decisions about whether and how such clauses will be used.

NCHRP Report 574: Guidance for Cost Estimation and Management for Highway Projects During Planning, Programming, and Preconstruction. Explores approaches to cost estimation and management designed to overcome the root causes of cost escalation and to support the development of consistent and accurate project estimates through all phases of the development process, from long-range planning through priority programming and project design.

NCHRP Report 658: Guidebook on Risk Analysis Tools and Management Practices to Control Transportation Project Costs. Explores specific, practical, and risk-related management practices and analysis tools designed to help manage and control transportation project costs.

"NCHRP 8-36 Task 72: Guidelines for Cost Estimation Improvements at State DOTs." Provides insights on how DOTs can implement strategies to effect the organizational and cultural changes necessary to improve the accuracy and consistency of project estimates.

"NCHRP Project 8-36(72): DOT Approaches to Implementing Cost Estimate Management Process Improvements." Documents the processes used by DOTs in implementing the accompanying guidebook developed for the project, and provides a technical reference on implementation from a synthesis of information gained from DOT implementation efforts.

Data

National Highway Cost Construction Index. FHWA provides a price index that can be used both to track price changes associated with highway construction costs and to convert current dollar expenditures on highway construction to real or constant dollar expenditures.

Highway Construction Cost/Inflation Issues. Contains archived information from FHWA regarding construction economics and price information, highway construction cost indices, state DOT material price indices, construction price adjustment clauses, and national highway construction price indexing information.

Office of Federal Lands Escalation Factors. Contains information from FHWA regarding fuel and asphalt escalation factors for contracts containing escalation clauses.

RSMeans. Publishes hard copy and electronic construction cost data.

Software

AASHTOWare Project Estimator. Developed by transportation officials, this program can be used to monitor costs, schedules, inventories, inspections, performance, displacements, and safety.

Bid Express. Online bid tool that can integrate with AASHTOWare or InfoTech's Appia for construction administration.

InfoTech Estimator Project Estimation. Developed for transportation agencies and consultants to estimate road and bridge project costs.

APPENDIX F

Unknown Recurrence Interval Calculator Tools

When conducting cost-benefit analyses (CBAs), analysts may base estimates of losses avoided from future events on similar, past events. They may know when the event occurred and how much damage transportation infrastructure sustained as a result of the event, but they may not know the recurrence interval of the event. Unknown recurrence interval calculators are tools that can help to estimate the recurrence interval of an event so that a CBA can be completed.

FEMA Damage Frequency Analysis Module

FEMA's Benefit-Cost Analysis software includes a Damage Frequency Analysis (DFA) module that allows the user to calculate project costs and benefits when the analyst does not have accurate or complete hazard or structural information. The FEMA DFA is relatively flexible; it can be used for a variety of hazard and project types and can be based on either historic or expected damages data. When using the Unknown Recurrence Interval (RI) calculator in the DFA to conduct an analysis using historic data, the user must have data for at least three events, and one of these events must have a known RI. When using the Unknown RI calculator in the DFA to conduct an analysis using expected damages data, the user must have at least one event, and all events used must have a known RI.

Additional information about the FEMA DFA module is available from FEMA's BCA website: https://www.fema.gov/media-library/assets/documents/18878. The FEMA BCA tool is a SQL server–based tool.

FTA Hazard Mitigation Cost-Effectiveness Tool

The FTA Hazard Mitigation Cost-Effectiveness (HMCE) tool uses a methodology similar to the FEMA DFA's Unknown RI approach to calculate unknown recurrence intervals. Similar requirements apply regarding the number and type of events (i.e., known versus unknown RIs) required to complete an analysis. The FTA HMCE tool is freely downloadable from the FTA Emergency Relief Program website and is an Excel-based spreadsheet tool rather than a SQL server–based tool (https://www.transit.dot.gov/funding/grant-programs/emergency-relief-program/hazard-mitigation-cost-effectiveness-tool). It was developed specifically for transit projects, but was designed to apply to a wider range of transportation projects.

APPENDIX G

Worksheet for Level 1 Analysis

The following presents a worksheet for Level 1 analysis.

Level 1: Climate-Adapted Benefit-Cost Analysis

This is an approximate test to see if it would be cost-effective to upgrade assets to the future conditions posed by climate change. This approach uses a number of variables in the calculations. A list of the variables that are used and their definitions is included in Table G-1.

Table G-1. List and definitions of variables used to conduct a CBA for climate-adapted assets.

Variable	Definition
T_{cnd}	Return period for which no damages occur
T_{cmod}	Next-highest return period after T_{cnd}; return period for which moderate damages are expected to occur
T_{cmax}	Return period for which damages are practically maximized
D_{cmod}	The amount of damages in dollars that are expected to occur as a result of a hazard event having a return period of T_{cmod}
D_{cmax}	The amount of damages in dollars that are expected to occur as a result of a hazard event having a return period of T_{cmax}
Q_{cnd}	Discharge flow in cfs associated with current conditions and no damages
Q_{cmod}	Discharge flow in cfs associated with current conditions and moderate damages
Q_{cmax}	Discharge flow in cfs associated with current conditions and maximum damages
D_{acmod}	Expected annualized damages for an event of moderate damage level under current conditions
D_{acmax}	Expected annualized damages for an event of severe damage level under current conditions
D_{ac}	Total expected annualized damages under current conditions
PVC	Present value coefficient
D_{Tc}	Present value of total expected damages under current conditions
T_{fnd}	Return period under future climate conditions for which no damages are expected to occur
T'_{fnd}	Return period under future climate conditions for which little damages are expected to occur
T_{fmod}	Return period under future climate conditions for which moderate damages are expected to occur

(continued on next page)

Table G-1. (Continued).

Variable	Definition
T_{fmax}	Return period under future climate conditions for which damages are expected to be practically maximized
Q_{fnd}	Flow under future climate conditions for which no damages are expected to occur
Q_{fmod}	Flow under future climate conditions for which moderate damages are expected to occur
Q_{fmax}	Flow under future climate conditions for which damages are expected to be practically maximized
D'_{fnd}	The amount of damages in dollars that are expected to occur as a result of a hazard event having a future return period of T'_{fnd}
D_{fmod}	The amount of damages in dollars that are expected to occur as a result of a hazard event having a future return period of T_{fmod}
D_{fmax}	The amount of damages in dollars that are expected to occur as a result of a hazard event having a future return period of T_{fmax}
D'_{afnd}	Expected annualized damages for an event of little damage level under future conditions
D_{afmod}	Expected annualized damages for an event of moderate damage level under future conditions
D_{afmax}	Expected annualized damages for an event of severe damage level under future conditions
D_{af}	Total expected annualized damages under future conditions
D_T	Additional damages associated with climate adjustment and no adaptation
T_{fint1}	Interpolated return period between a return period associated with little damages and one associated with moderate damages under future climate conditions
T_{fint2}	Interpolated return period between a return period associated with moderate damages and one associated with maximum damages under future climate conditions
D_{afint1}	Expected annualized damages for an event having a return period of T_{fint1}
D_{afint2}	Expected annualized damages for an event having a return period of T_{fint2}
Tide El_{cnd}	Flood elevation associated with no damages from tidal flooding under current conditions
Tide El_{cmod}	Tidal flood elevation associated with moderate damages under current conditions
Tide El_{cmax}	Tidal flood elevation associated with maximized damages under current conditions
Tide El_{fnd}	Flood elevation associated with no damages from tidal flooding under future conditions
Tide El'_{fnd}	Flood elevation associated with little damages from tidal flooding under future conditions
Tide El_{fmod}	Flood elevation associated with moderate damages from tidal flooding under future conditions
Tide El_{fmax}	Flood elevation associated with maximized damages from tidal flooding under future conditions

External Data Requirements

Parameter	Value Used in Scenario	Data Source(s)
Facility of concern	Culvert	Project file
Geographic location of the facility/corridor under consideration	Chesterfield, VA	Site plan, maps
Hazard(s) of concern	Flood	Hazard analysis
Current design criteria—flow rate	9,000 cfs	Engineering designs and plans
Current design criteria—recurrence interval	50-year event	AASHTO design manual, DOT design manual
Discount rate(s) to be used in the analysis	7%	OMB A-94
Expected useful life of current facility	Within 2 years	Capital plan, O&M records
Expected useful life of replacement facility	50	Virginia DOT design guides
Anticipated time frame for implementation of adaptation strategies	2 years	Capital plan
Scenario(s) to be used for analysis	Precipitation conditions in 2049	NOAA Atlas 14, SWMM-CAT for warmer, wetter conditions 2045–2075
Design concepts of adaptation strategies	Enlarge culvert, add multiple culverts, use box or arch culvert	Engineering department
Cost estimate for each adaptation strategy (life-cycle costs, including any long-term adverse impacts from the adaptation strategy)	Cost estimates	Historical data, recent bids for similar work, cost-estimating software
Identification of any non-quantifiable costs associated with the project	None	DOT analysis
Estimates of damages sustained from the hazard of concern	Loss estimates	Historical data, engineering analyses, O&M records, depth-damage curves
Estimates of additional benefits resulting from the project, separated by physical/social/environmental if using multiple discount rates	Benefits estimates	FEMA benefit-cost analysis tools for drought, ecosystem services, and post-wildfire mitigation
Identification of any non-quantifiable benefits associated with the project	None	DOT analysis

Current Conditions

Step 1. Determine return periods.		
Description	**Variable**	**Value**
Largest return period for which there will be no damage (Design Return Period)	T_{cnd} **(years)**	50
Return period associated with an event that would cause moderate but considerable structural damage or roadway flooding and traffic interruption. This would be the next-highest standard return period to T_{nd}	T_{cmod} **(years)**	100
Return period for which damages would be practically maximized	T_{cmax}**(years)**	500

Step 2. Determine damages associated with Step 1.		
Total damages associated with T_{cnd}	**D_{cnd} ($)**	0
Total damages associated with T_{cmod} (e.g., loss of riprap, short-term road closure, traffic control and road cleanup costs)	**D_{cmod} ($)**	1,630,000
Total damages associated with T_{cmax} (i.e., failure of the hydraulic structure leading to large structural damage and loss of road service and possibly injuries or fatalities)	**D_{cmax} ($)**	3,227,000
Present value coefficient for the remaining project useful life (i.e., remaining service life during the period of projected climate change) from Appendix B	**PVC (%)**	13.801

Step 3. Determine current discharge flows associated with Step 2.		
Associate discharges with return period, T_{cnd} under current (no climate change) conditions	**Q_{cnd} (cfs)**	9,000
Associate discharges with return period, T_{cmod} under current (no climate change) conditions	**Q_{cmod} (cfs)**	10,505
Associate discharges with T_{cmax} under current (no climate change) conditions	**Q_{cmax} (cfs)**	13,982

Step 4. Calculate expected annual damages between T_{cnd} and T_{cmod} based on Step 1 and Step 2.

$$D_{acmod} = \frac{D_{cnd}+D_{cmod}}{2} * \left(\frac{1}{T_{cnd}} - \frac{1}{T_{cmod}}\right)$$

$$D_{acmod} = \frac{0 + 1{,}630{,}000}{2} * \left(\frac{1}{50} - \frac{1}{100}\right)$$

$$D_{acmod} = 815{,}000 * 0.01 = 8{,}150$$

$$D_{acmod} = \$8{,}150$$

Step 5. Calculate expected annual damages between T_{cmod} and T_{cmax} based on Step 1 and Step 2.

$$D_{acmax} = \frac{D_{cmod}+D_{cmax}}{2} * \left(\frac{1}{T_{cmod}} - \frac{1}{T_{cmax}}\right)$$

$$D_{acmax} = \frac{1{,}630{,}000 + 3{,}227{,}000}{2} * \left(\frac{1}{100} - \frac{1}{500}\right)$$

$$D_{acmax} = 2{,}428{,}500 * 0.008 = 19{,}428$$

$$D_{acmax} = \$19{,}428$$

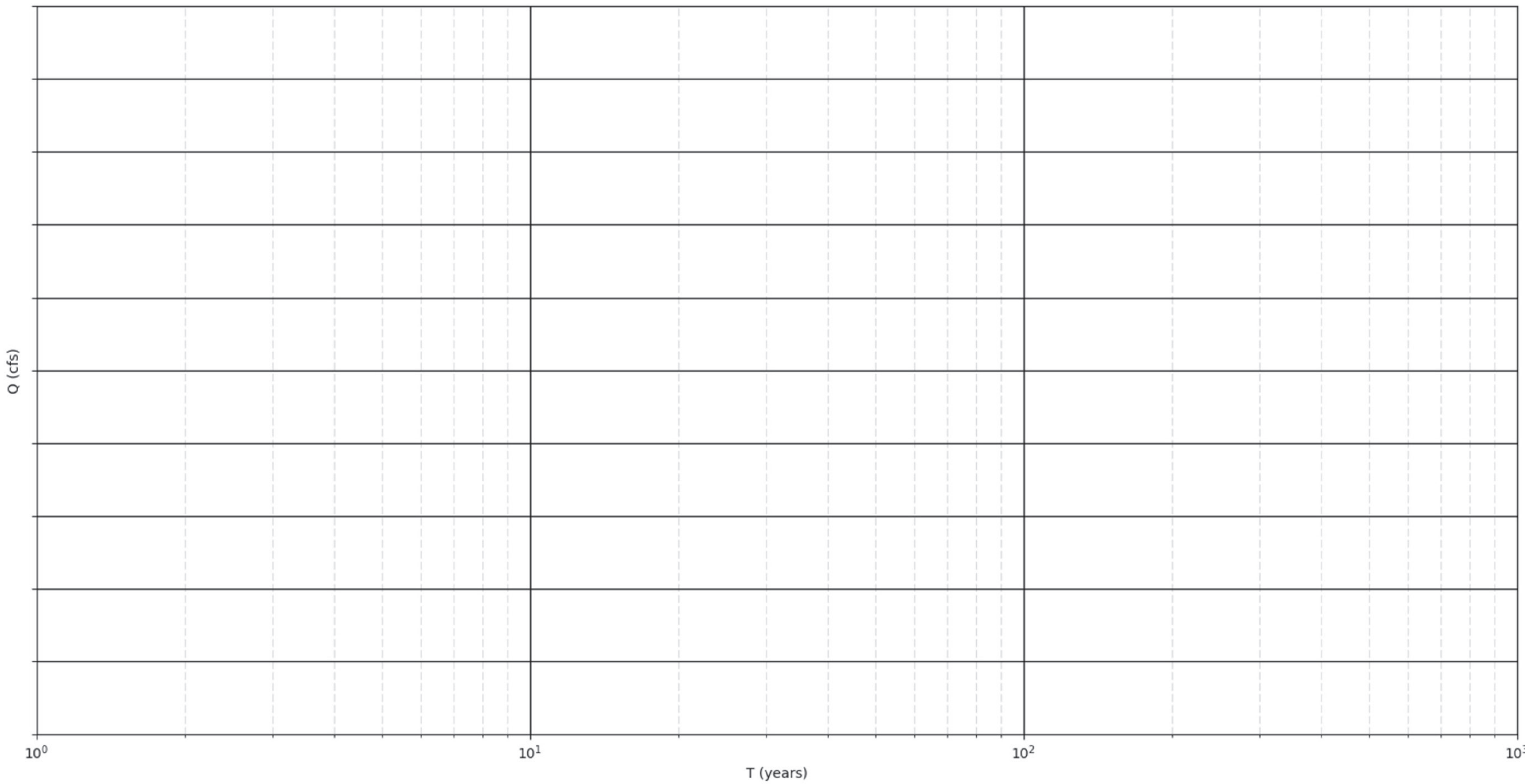
Step 6. Calculate total annualized damages.
$D_{ac} = D_{acmod} + D_{acmax}$
D_{ac} = \$8,150 + \$19,428 = \$27,578
D_{ac} = \$27,578

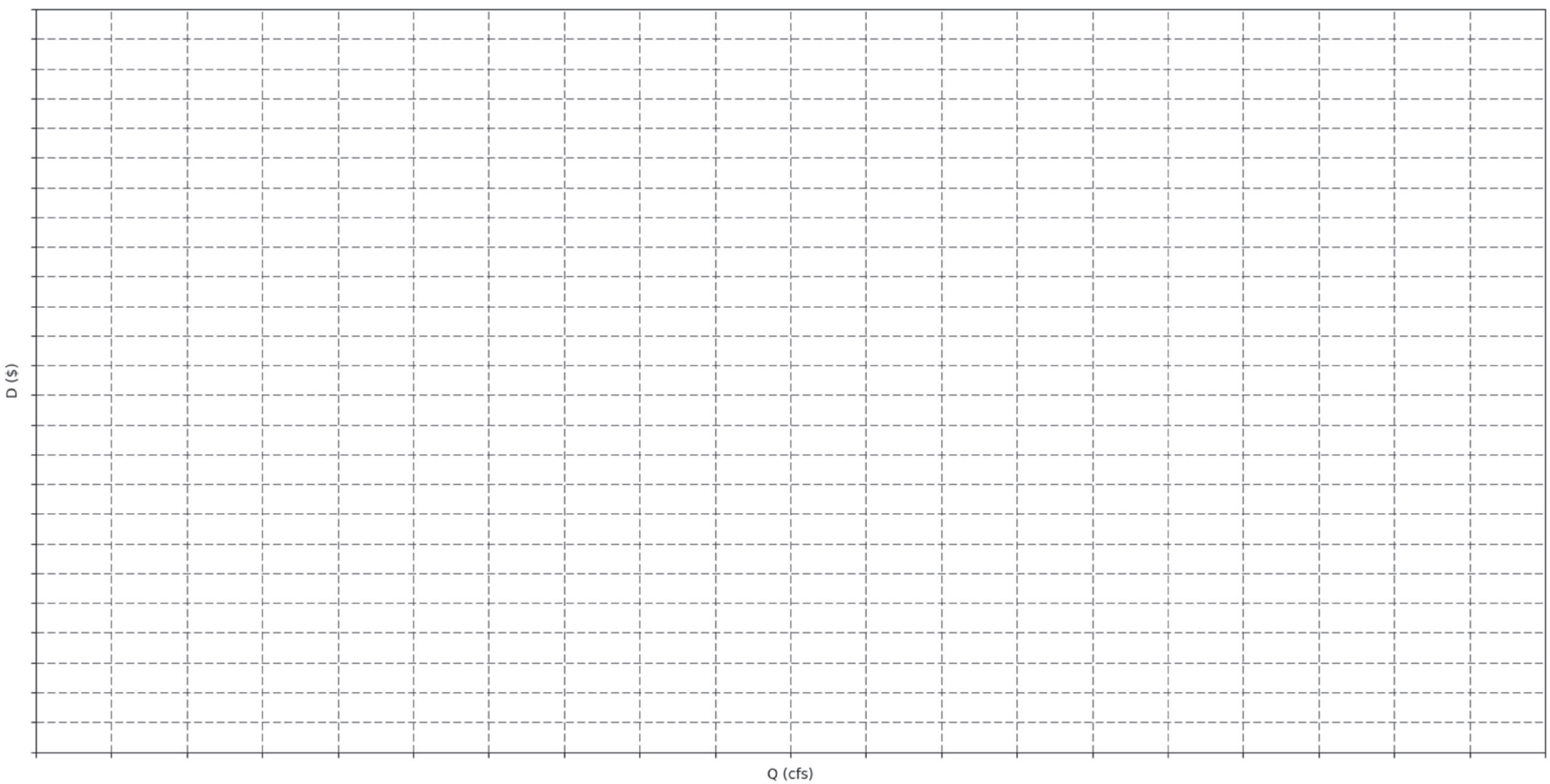
Step 7. Calculate present value of total expected damages under current conditions.
$D_{Tc} = D_{ac} * PVC$
D_{Tc} = 27,578 *13.801
D_{Tc} = \$380,604
Note: PVC can be determined based on Appendix B.

Step 8. Summarize the data for current climate conditions.				
	T_c(years)	D_c(\$)	Q_c(cfs)	D_{ac}(\$)
T_{cnd}	50	0	9,000	0
T_{cmod}	100	1,630,000	10,505	8,150
T_{cmax}	500	3,227,000	13,982	19,428
Total annualized damages				27,578

Step 9. Plotting

- Create a graph by plotting the return periods T_{cnd}, T_{cmod}, and T_{cmax} (Step 8) on a logarithmic scale on the *x*-axis against the associated discharges on the *y*-axis.
- Create a second graph by plotting the discharges on the *x*-axis (with a "normal" scale as opposed to logarithmic) and the estimated damages (D) (Step 8) associated with each discharge on the *y*-axis.


Q (cfs)
10^0
10^1
10^2
10^3
T (years)


D ($)
Q (cfs)

Calculate future flows and associated expected damages for future climate conditions. To do this, start by identifying the climate change scenario to be used for analysis (see Chapter 3). For the selected climate scenario, calculate the estimated future discharges for each return period (i.e., return period in which no damages occur, return period in which moderate damages occur, and return period in which significant damages occur). This will result in identifying values for Q_{f1}, Q_{f3}, and Q_{f5}.

Step 10. Calculate the future flows for selected return periods.		
Description	**Variable**	**Value**
Associate discharges with return period, T_{fnd} (i.e., T_{cnd}) based on climate change conditions	$\mathbf{Q_{fnd}}$	9,979
Associate discharges with return period, T_{fmod} (i.e., T_{cmod}) based on climate change conditions	$\mathbf{Q_{fmod}}$	11,665
Associate discharges with T_{fmax} (i.e., T_{cmax}) based on based on climate change conditions	$\mathbf{Q_{fmax}}$	15,562

Step 11. Plotting: Summarize the current and future flows for each return period.			
T_c(years)*	**Q_c (cfs)***	**T_f (years)**	**Q_f (cfs)**
50	9,000	50	9,979
100	10,505	100	11,665
500	13,982	500	15,562

*See Step 8

Plot the future discharges under the selected climate change scenario Q_{fnd}, Q_{fmod}, and Q_{fmax} on the same logarithmic graph as the baseline conditions (see Step 9).

Step 12. Calculate the future return period for the selected climate scenario based on Step 11. This provides an estimate of the climate-adjusted return period for the base flow.

$$Log\ T_{fnd} = logT_{fmod} - \left(Log\ T_{fmod} - Log\ T_{fnd}\right) * \frac{Q_{fmod} - Q_{cnd}}{Q_{fmod} - Q_{fnd}}$$

and

$$T_f = 10^{\ Log\ T_f}$$

$$Log\ T_{fnd} = \log(100) - \ (Log\ 100 - \ Log\ 50) * \frac{11{,}665 - 9{,}000}{11{,}665 - 9{,}979}$$

$$Log\ T_{fnd} = 2 - \ (2 - 1.699\ ) * 1.58$$

$$Log\ T_{fnd} = 2 - 0.476$$

$$Log\ T_{fnd} = 1.524$$

$$T_f = 33.4\ Years$$

Step 13. Interpolate the damages (D'_{fnd}) linearly based on revised future discharges (Step 11) using the equations below.

$$D'_{fnd} = D_{cnd} + \frac{(Q_{fnd} - Q_{cnd})}{(Q_{cmod} - Q_{cnd})} * (D_{cmod} - D_{cnd})$$

$$D'_{fnd} = 0 + \frac{(9{,}979 - 9{,}000\ \ )}{(10{,}505 - 9{,}000)} * (1{,}630{,}000 - 0)$$

$$D'_{fnd} = 0.65 * 1{,}630{,}000$$

$$D'_{fnd} = \$1{,}060{,}312$$

Step 14. Interpolate the damages (D_{fmod}) linearly based on revised future discharges (Step 11) using the equations below.

$$D_{fmod} = D_{cmod} + \frac{(Q_{fmod} - Q_{cmod})}{(Q_{cmax} - Q_{cmod})} * (D_{cmax} - D_{cmod})$$

$$D_{fmod} = 1{,}630{,}000 + \frac{(11{,}665 - 10{,}505\ \ )}{(13{,}982 - 10{,}505)} * (3{,}227{,}000 - 1{,}630{,}000)$$

$$D_{fmod} = 1{,}630{,}000 + 0.334 * 1{,}597{,}000$$

$$D_{fmod} = 1{,}630{,}000 + 533{,}398$$

$$D_{fmod} = \$2{,}162{,}793$$

Step 15. Interpolate the damages (D_{fmax}) linearly based on revised future discharges (Step 11) using the equations below.

$$D_{fmax} = D_{cmax} + \frac{(Q_{fmax} - Q_{cmax})}{Q_{cmax}} * D_{cmax}$$

$$D_{fmax} = 3{,}227{,}000 + \frac{(15{,}562 - 13{,}982\ \ )}{13{,}982} * 3{,}227{,}000$$

$$D_{fmax} = 3{,}227{,}000 + 0.113 * 3{,}227{,}000$$

$$D_{fmax} = 3{,}227{,}000 + 364{,}651$$

$$D_{fmax} = \$3{,}591{,}659$$

Step 16. Summarize the climate-adjusted values for discharge and damages. Set the future damages (D_{fnd}) corresponding to T_{fnd} to $0, as this value corresponds to the same discharge as Q_{cnd} (i.e., $Q_{cnd} = Q_{fnd}$) .

	T_f	D_f ($)	Q_f (cfs)
T_{fnd}	33.4	0	9,000
T'_{fnd}	50	1,060,312	9,979
T_{fmod}	100	2,162,793	11,665
T_{fmax}	500	3,591,659	15,562

Step 17. Plot the damages against the peak discharges on the same regular graph paper as for the previous figure to develop a curve for climate-adjusted flows.

Step 18. Calculate the annualized damages for climate-adjusted conditions using a similar approach to the previous section, substituting the climate-adjusted values for the current condition values based on Step 16.

$$D'_{afnd} = \frac{D_{fnd}+D'_{fnd}}{2} * \left(\frac{1}{T_{fnd}} - \frac{1}{T'_{fnd}}\right)$$

$$D'_{afnd} = \frac{(\$0 + \$1{,}060{,}312\ )}{2} * \left(\frac{1}{33.4} - \frac{1}{50}\right)$$

$$D'_{afnd} = 530{,}156 * 0.00994$$

$$D'_{afnd} = \$5{,}270$$

Step 19. Calculate the annualized damages for climate-adjusted conditions using a similar approach to the previous section, substituting the climate-adjusted values for the current condition values based on Step 16.

$$D_{afmod} = \frac{D'_{fnd} + D_{fmod}}{2} * \left(\frac{1}{T'_{fnd}} - \frac{1}{T_{fmod}}\right)$$

$$D_{afmod} = \frac{(\$1{,}060{,}312 + \$2{,}162{,}793\ )}{2} * \left(\frac{1}{50} - \frac{1}{100}\right)$$

$$D_{afmod} = 1{,}611{,}553 * 0.01$$

$$D_{afmod} = \$16{,}116$$

Step 20. Calculate the annualized damages for climate-adjusted conditions using a similar approach to the previous section, substituting the climate-adjusted values for the current condition values based on Step 16.

$$D_{afmax} = \frac{D_{fmod} + D_{fmax}}{2} * (\frac{1}{T_{fmod}} - \frac{1}{T_{fmax}})$$

$$D_{afmax} = \frac{(\$2{,}162{,}793 + \$3{,}591{,}659\ )}{2} * \left(\frac{1}{100} - \frac{1}{500}\right)$$

$$D_{afmax} = 2{,}877{,}226 \quad 0.008$$

$$D_{afmax} = \$23{,}018$$

Step 21. Calculate the annualized damages for climate-adjusted conditions using a similar approach to the previous section, substituting the climate-adjusted values for the current condition values.

$$D_{af} = D'_{afnd} + D_{afmod} + D_{afmax}$$

$$D_{af} = 5{,}270 + 16{,}116 + 23{,}018$$

$$D_{af} = \$44{,}404$$

Step 22. Calculate the annualized damages for climate-adjusted conditions using a similar approach to the previous section, substituting the climate-adjusted values for the current condition values.

$$D_{Tf} = D_{af} * PVC$$

$$D_{Tf} = \$44{,}404 * 13.801$$

$$D_{Tf} = \$612{,}820$$

Step 23. Summarize the climate-adjusted values.

	T_f	Q_f (cfs)	D_f($)	D_{af}($)
T_{fnd}	33	9,000	0	0
T'_{fnd}	50	9,979	1,060,312	5,270
T_{fmod}	100	11,665	2,162,793	16,116
T_{fmax}	500	15,562	3,591,659	23,018

Step 24. Compare the additional damages for the base case with and without climate adjustment using the base case damages calculated in Step 7 and climate-adjusted damages calculated in Step 22.

$$\Delta D_T = D_{Tf} - D_{Tc}$$

$$\Delta D_T = 612{,}820 - 380{,}604$$

$$\Delta D_T = \$232{,}216$$

This value represents the additional present value of the expected damages from climate change during the asset's remaining useful life. A resilience/mitigation measure aimed at maintaining the current frequency-damage structure (design level) while accounting for climate change must cost less than this value to be cost-effective.

APPENDIX H

Worksheet for Level 2 Analysis

The following presents a worksheet for Level 2 analysis.

Level 2: Climate-Adapted Benefit-Cost Analysis

Level 2 analysis builds on Level 1 analysis. A Level 2 analysis uses existing conditions without climate change only to calculate the new return period for future conditions with climate change, that is, the maximum return period under climate change conditions for which no damages will occur, T_f. A Level 2 analysis then calculates future damages under climate change conditions without and with resilience/mitigation measures in place.

Step 1. Summarize results of Study Level 1 in the table that follows.

	Current pre-mitigation conditions				**Future (climate change) pre-resilience**			
					Return period	**Future discharge**	**Interpolated damages**	**Base case future damage increment**
	Return period	**Damages (in current $)**	**Damage increment**	**Current discharge**	T_{fnd}=33	Q_{fnd}= 9,000	D_{fnd}=0	D_{afnd} =0
Max return period resulting in no damages	T_{cnd} =50	D_{cnd}=0	D_{acnd}=0	Q_{cnd}=9,000	T'_{fnd}= 50	Q'_{fnd}=9,979	D'_{fnd}=1,060,312	D'_{afnd}=5,270
Next level return period resulting in some damages	T_{cmod}=100	D_{cmod}=1,630,000	D_{acmod}=8,150	Q_{cmod}=10,505	T_{fmod}= 100	Q_{fmod}=11,665	D_{fmod}=2,162,793	D_{afmod}=16,116
Return period resulting in maximum damages	T_{cmax}=500	D_{cmax}=3,227,000	D_{acmax}=19,428	Q_{cmax}=13,982	T_{fmax}= 500	Q_{fmax}=15,562	D_{fmax}=3,591,659	D_{afmax}=23,018

Step 2. Add points to Future Discharges and Damage curves. Adding more points for the discharge versus return period and damages versus discharge graphs will correct for discrepancies between existing conditions and future climate conditions. Use the following equations to calculate climate-adjusted return periods (T_{fint1}) for Q_{cmod} based on Step 1.

$$Log\ T_{fint1} = \text{Log}(T_{fmod}) - \left(Log\ (T_{fmod}) - Log(\ T'_{fnd})\right) * \frac{Q_{fmod} - Q_{cmod}}{Q_{fmod} - Q'_{fnd}}$$

$$Log\ T_{fint} = \text{Log}(100) - \left(Log\ (100) - Log(\ 50)\right) * \frac{11{,}665 - 10{,}505}{11{,}665 - 9{,}979}$$

$$Log\ T_{fint1} = 2 - \ (2 - 1.699\ ) * 0.688$$

$$Log\ T_{fint1} = 2 - 0.207$$

$$Log\ T_{fint1} = 1.793$$

T_{fint1} = 62 years

Step 3. Add points to Future Discharges and Damages. Adding more points for the discharge versus return period and damages versus discharge graphs will correct for discrepancies between existing conditions and future adapted conditions. Use the following equations to calculate climate-adapted return periods (T_{fint2}) for Q_{cmax} based on Step 1.

$$Log\ T_{fint2} = \text{log}(T_{fmax}) - \left(Log\ (T_{fmax}) - Log(\ T_{fmod})\right) * \frac{Q_{fmax} - Q_{cmax}}{Q_{fmax} - Q_{fmod}}$$

$$Log\ T_{fin} = \text{log}(500) - \left(Log\ (500) - Log(100)\right) * \frac{15{,}562 - 13{,}982}{15{,}562 - 11{,}665}$$

$$Log\ T_{fint} = 2.699 - \ (2.699 - 2\ ) * 0.405$$

$$Log\ T_{fint2} = 2.699 - \ (2.699 - 2\ ) * 0.405$$

$$Log\ T_{fint2} = 2.699 - 0.283$$

$$Log\ T_{fint2} = 2.416$$

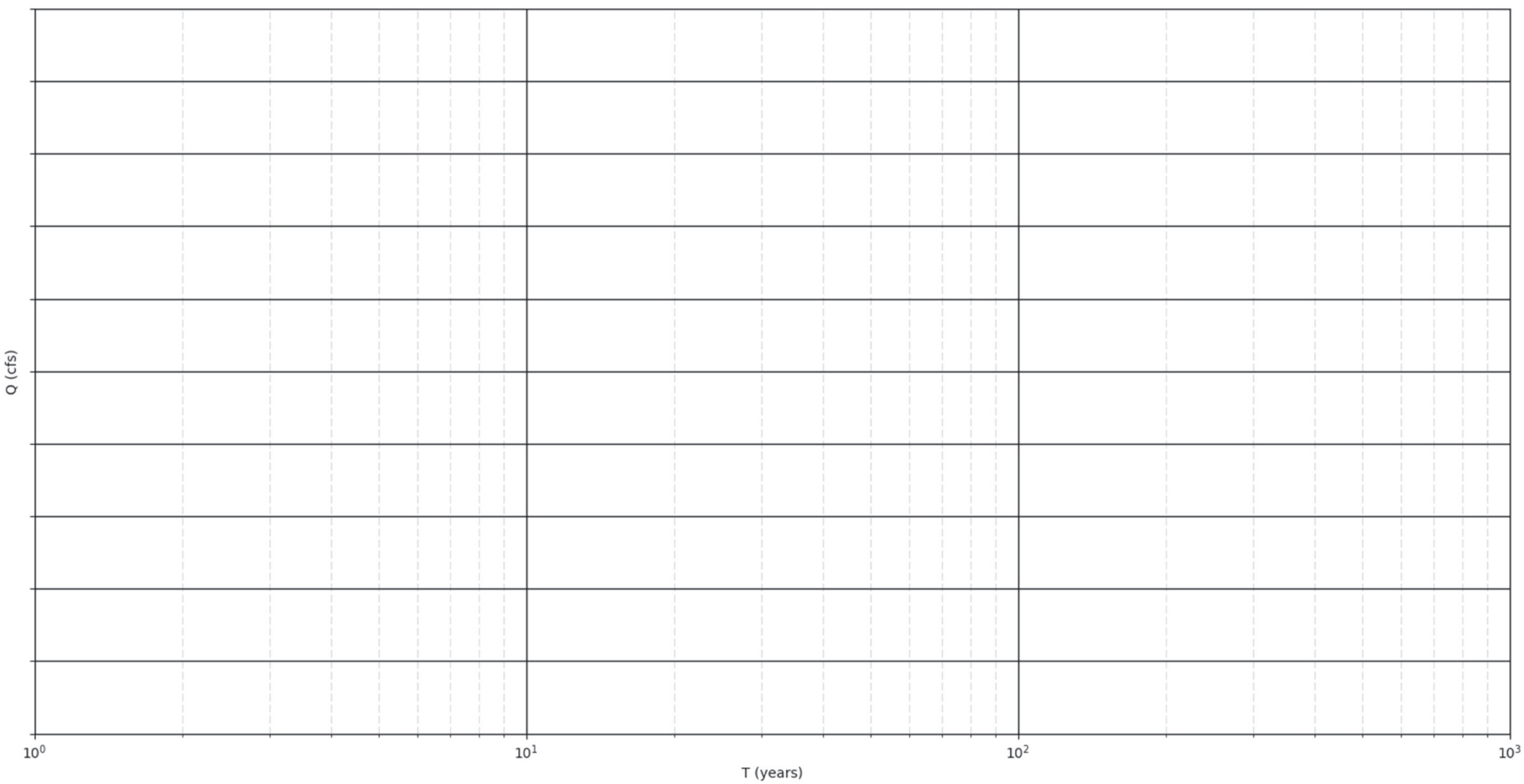
T_{fint2} = 260 years

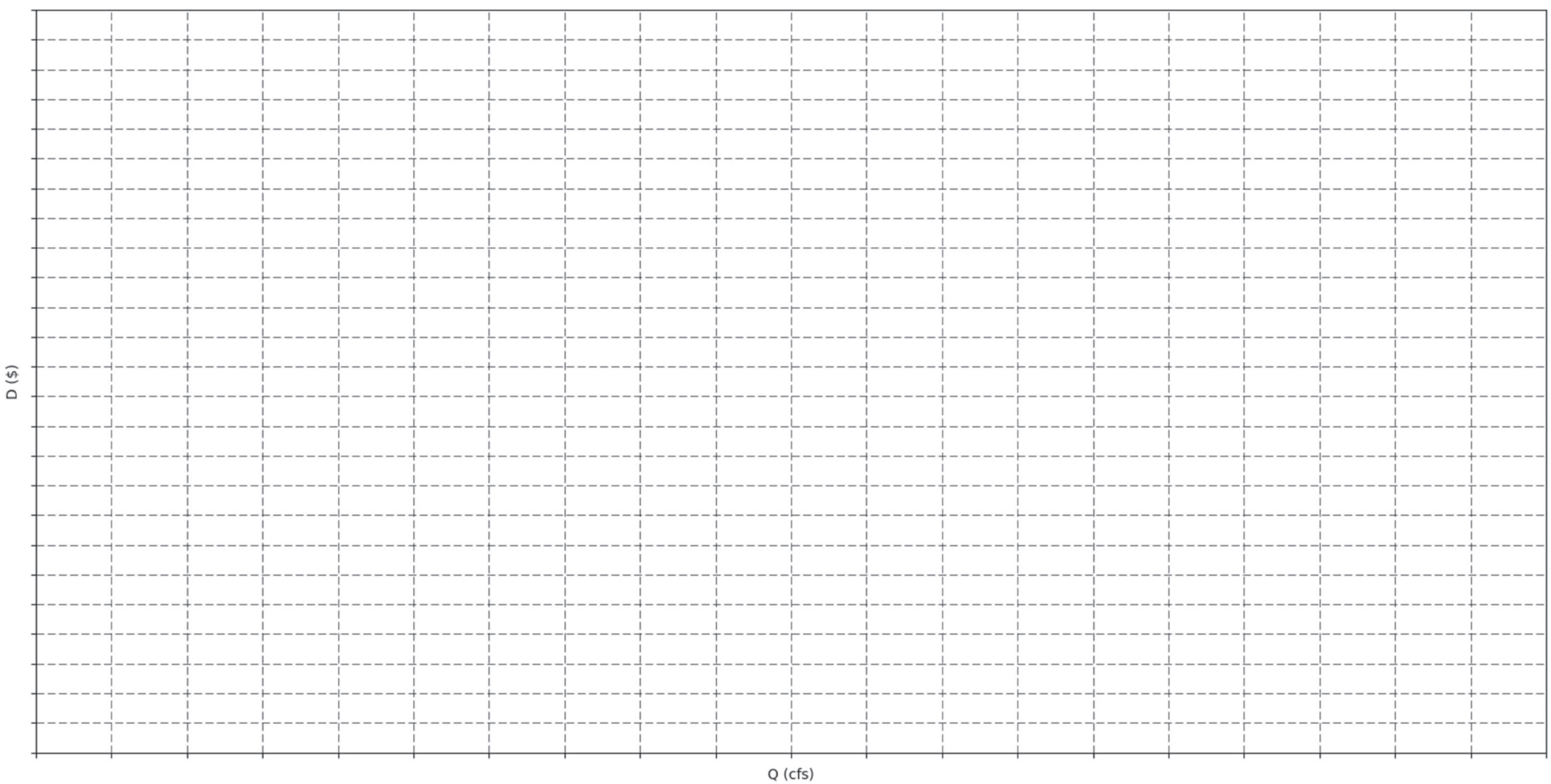
Step 4. Summarize the results in the table below. The results in step 2 and 3 assume that under climate change conditions T_{fint1} will have the same flow as Q_{cmod} and T_{fint2} will have the same flow as Q_{cmax}. The damages for these newly calculated return periods in T_{fint1} and T_{fint2} will have the same value as the original periods of T_{cmod} and T_{cmax} (i.e., D_{cmod} and D_{cmax}).

	Current pre-mitigation conditions				Future (climate change) pre-resilience			
					Return period	**Future discharge**	**Interpolated damages**	**Base case future damage increment**
	Return period	**Damages (in current $)**	**Damage increment**	**Current discharge**	T_{fnd}=33	Q_{fnd}= 9,000	D_{fnd}=0	D_{afnd}=0
Max return period resulting in no damages	T_{cnd} =50	D_{cnd}=0	D_{acnd}=0	Q_{cnd}=9,000	T'_{fnd}= 50	Q'_{fnd}=9,979	D'_{fnd}=1,060,312	D'_{afnd}=5,270
Next level return period resulting in some damages	T_{cmod}=100	D_{cmod}=1,630,000	D_{acmod}=8,150	Q_{cmod}=10,505	T_{fint1} = 62	Q_{fint1}=10,505	D_{fint1}= 1,630,000	D_{afint1}= 8,150
Return period resulting in maximum damages	T_{cmax}=500	D_{cmax}=3,227,000	D_{acmax}=19,428	Q_{cmax}=13,982	T_{fmod}= 100	Q_{fmod}=11,665	D_{fmod}=2,162,793	D_{afmod}=16,116
					T_{fint2} = 260	Q_{fint2}=13,982	D_{fint2}= 3,227,000	D_{afint2}=19,428
					T_{fmax}= 500	Q_{fmax}=15,562	D_{fmax}=3,591,659	D_{afmax}=23,018

Step 5. Based on Step 4, plot the additional flows and return periods on the log graph (Return Period versus Discharge curve) and the damages and discharges on the second plot (Discharge versus Damages curve) from Level 1 for future conditions for the two additional points. (Graph paper provided on next pages.)

Step 6. Next, the analysis adds the impacts that a resilience/adaptation action could have on damages to the asset after the resilience action has been implemented to accommodate the modeled climate change conditions. The analysis assumes that resilience action will eliminate future damages under climate change conditions for the future T'_{fnd} (i.e., same as current level without climate change), and the damages for the post-resilience future T_{fmod} and T_{fmax} events (i.e., without climate change). It is assumed that the resilience action taken will restore the climate-adjusted conditions to mirror existing conditions, meaning the post-resilience values of damages for the climate-adjusted 100- and 500-year return periods are assumed to be equal to the level of damages under current conditions. Summarize the assumptions in the table that follows the graph paper.


Q (cfs)
10^0
10^1
10^2
10^3
T (years)


D ($)
Q (cfs)

	Current pre-mitigation conditions				**Future (climate change) pre-resilience**				**Future post-resilience**			
					Return period	**Future discharge**	**Interpolated damages**	**Base case future damage increment**	**Return period**	**Future discharge**	**Damages (in current $)**	**Base case future damage increment**
	Return period	**Damages (in current $)**	**Damage increment**	**Current discharge**	T_{fnd}=33	Q_{fnd}= 9,000	D_{fnd}=0	D_{afnd}= 0	T_{rnd}=33	Q_{rnd}=0	D_{rnd}=0	D_{arnd}=0
Max return period resulting in no damages	T_{cnd} =50	D_{cnd}=0	D_{acnd}=0	Q_{cnd}=9,000	T'_{fnd}= 50	Q'_{fnd}=9,979	D'_{fnd}= 1,060,312	D'_{afnd}=5,270	T'_{rnd}=50	Q'_{rnd}= 9,979	D'_{rnd}=0	D'_{arnd}=0
Next level return period resulting in some damages	T_{cmod}= 100	D_{cmod}= 1,630,000	D_{acmod}= 8,150	Q_{cmod}= 10,505	T_{fint1} = 62	Q_{fint1}=10,505	D_{fint1}= 1,630,000	D_{afint1}= 8,150	T_{rint1}=62	Q_{rmod}=10,505		
Return period resulting in maximum damages	T_{cmax}= 500	D_{cmax}= 3,227,000	D_{acmax}= 19,428	Q_{cmax}= 13,982	T_{fmod}= 100	Q_{fmod}=11,665	D_{fmod}= 2,162,793	D_{afmod}=16,116	T_{rmod}=100	Q_{rmod}=11,665	D_{rmod}= 1,630,000	
					T_{fint2} = 260	Q_{fint2}=13,982	D_{fint2}= 3,227,000	D_{afint2}=19,428	T_{rint2}=260	Q_{rint2}=13,982		
					T_{fmax}= 500	Q_{fmax}=15,562	D_{fmax}= 3,591,659	D_{afmax}=23,018	T_{rmax}=500	Q_{rmax}=15,562	D_{rmax}= 3,227,000	

Step 7. Determine the damages for T_{rint1} using the assumption in Step 6.

$$D_{rint1} = D'_{rnd} + \frac{(Q_{rmod} - Q'_{rnd}) * (D_{rmod} - D'_{rnd})}{Q_{rmod} - Q'_{rnd}}$$

$$D_{rint} = 0 + \frac{(10{,}505 - 9{,}979\ \ ) * (1{,}630{,}000 - 0\ \ )}{11{,}665 - 9{,}979}$$

$$D_{rint1} = 0 + \frac{526 * 1{,}630{,}000}{1{,}686}$$

$$D_{rint1} = 0 + \frac{526 * 1{,}630{,}000}{1{,}686}$$

$$D_{rint} = 0 + 508{,}529$$

$$D_{rint1} = \$508{,}529$$

Step 8. Determine the damages for T_{rint2} using the assumption in Step 6.

$$D_{rint2} = D_{rmax} + \frac{(Q_{rint2} - Q_{rmod}) * (D_{rmax} - D_{rmod})}{Q_{rmax} - Q_{rmod}}$$

$$D_{rint2} = 1{,}630{,}000 + \frac{(13{,}982 - 11{,}665\ \ ) * (3{,}227{,}000 - 1{,}630{,}000\ \ )}{15{,}562 - 11{,}665}$$

$$D_{rint} = 1{,}630{,}000 + \frac{2{,}317 * 1{,}597{,}000}{3{,}897}$$

$$D_{ri} = 1{,}630{,}000 + 949{,}512$$

$$D_{rint2} = \$2{,}579{,}512$$

Step 9. Determine the annualized damages for T_{rint1} using the assumption in Step 6.

$$D_{arin} = \frac{D'_{rnd} + D_{rint}}{2} * \left(\frac{1}{T'_{rnd}} - \frac{1}{T_{rint}}\right)$$

$$D_{arint1} = \frac{0 + 508{,}529}{2} * \left(\frac{1}{50} - \frac{1}{62}\right)$$

$$D_{arint} = 254{,}265 * 0.0039$$

$$D_{arint1} = \$984$$

Step 10. Determine the annualized damages for T_{rmod} using the assumption in Step 6.

$$D_{armod} = \frac{D_{rint1} + D_{rmod}}{2} * \left(\frac{1}{T_{rint1}} - \frac{1}{T_{rmod}}\right)$$

$$D_{armod} = \frac{508{,}529 + 1{,}630{,}000}{2} * \left(\frac{1}{62} - \frac{1}{100}\right)$$

$$D_{armod} = 1{,}069{,}265 * 0.0061$$

$$D_{armod} = \$6{,}554$$

Step 11. Determine the annualized damages for T_{rint2} using the assumption in Step 6.

$$D_{arint2} = \frac{D_{rmod} + D_{rint2}}{2} * \left(\frac{1}{T_{rmod}} - \frac{1}{T_{rint2}}\right)$$

$$D_{arint2} = \frac{1{,}630{,}000 + 2{,}579{,}512}{2} * \left(\frac{1}{100} - \frac{1}{260}\right)$$

$$D_{arint2} = 2{,}104{,}756 * 0.00615$$

$$D_{arint2} = \$12{,}952$$

Step 12. Determine the annualized damages for T_{rmax} using the assumption in Step 6.

$$D_{armax} = \frac{D_{rint2} + D_{rmax}}{2} * \left(\frac{1}{T_{rint2}} - \frac{1}{T_{rmax}}\right)$$

$$D_{armax} = \frac{2{,}579{,}512 + 3{,}227{,}000}{2} * \left(\frac{1}{260} - \frac{1}{500}\right)$$

$$D_{armax} = 2{,}903{,}256 * 0.00185$$

$$D_{armax} = \$5{,}360$$

Step 13. Summarize the results in the table below.

	Current pre-mitigation conditions				**Future (climate change) pre-resilience**				**Future post-resilience**			
					Return period	**Future discharge**	**Interpolated damages**	**Base case future damage increment**	**Future discharge**	**Return period**	**Damages (in current $)**	**Base case future damage increment**
	Return period	**Damages (in current $)**	**Damage increment**	**Current discharge**	$T_{fnd}=33$	$Q_{fnd}=9{,}000$	$D_{fnd}=0$	$D_{afnd}=0$	$T_{rnd}=33$	$Q_{rnd}=0$	$D_{rnd}=0$	$D_{arnd}=0$
Max return period resulting in no damages	$T_{cnd}=50$	$D_{cnd}=0$	$D_{acnd}=0$	$Q_{cnd}=9{,}000$	$T'_{fnd}=50$	$Q'_{fnd}=9{,}979$	$D'_{fnd}=1{,}060{,}312$	$D'_{afnd}=5{,}270$	$T'_{rnd}=50$	$Q'_{rnd}=9{,}979$	$D'_{rnd}=0$	$D'_{arnd}=0$
Next level return period resulting in some damages	$T_{cmod}=100$	$D_{cmod}=1{,}630{,}000$	$D_{acmod}=8{,}150$	$Q_{cmod}=10{,}505$	$T_{fint1}=62$	$Q_{fint1}=10{,}505$	$D_{fint1}=1{,}630{,}000$	$D_{afint1}=8{,}150$	$T_{rint1}=62$	$Q_{rmod}=10{,}505$	$D_{rint1}=508{,}529$	$D_{arint1}=984$
Return period resulting in maximum damages	$T_{cmax}=500$	$D_{cmax}=3{,}227{,}000$	$D_{acmax}=19{,}428$	$Q_{cmax}=13{,}982$	$T_{fmod}=100$	$Q_{fmod}=11{,}665$	$D_{fmod}=2{,}162{,}793$	$D_{afmod}=16{,}116$	$T_{rmod}=100$	$Q_{rmod}=11{,}665$	$D_{rmod}=1{,}630{,}000$	$D_{armod}=6{,}554$
					$T_{fint2}=260$	$Q_{fint2}=13{,}982$	$D_{fint2}=3{,}227{,}000$	$D_{afint2}=19{,}428$	$T_{rint2}=260$	$Q_{rint2}=13{,}982$	$D_{rint2}=2{,}579{,}512$	$D_{arint2}=12{,}952$
					$T_{fmax}=500$	$Q_{fmax}=15{,}562$	$D_{fmax}=3{,}591{,}659$	$D_{afmax}=23{,}018$	$T_{rmax}=500$	$Q_{rmax}=5{,}562$	$D_{rmax}=3{,}227{,}000$	$D_{armax}=5{,}360$

Step 14. Calculate the total annualized future damages for the post-resilience action by adding the annualized incremental damages for the different return period.

$$D_{ar} = D_{arnd} + D'_{arnd} + D_{arint1} + D_{armod} + D_{arint2} + D_{armax}$$

$$D_{ar} = 0 + 0 + 984 + 6{,}554 + 12{,}952 + 5{,}360$$

$$D_{ar} = \$25{,}850$$

Step 15. Multiply the total annualized future damages after resilience measures that have been implemented (Step 14) by the present value factor.

$$D_{Tr} = D_{ar} * PVC$$

$$D_{Tr} = 25{,}850 * 13.801$$

$$D_{Tr} = \$356{,}756$$

Step 16. Subtract the post-resilience total damages (Step 15) from the pre-resilience total damages under climate change conditions (Step 22 from Level 1 analysis) to yield the present value of the benefits associated with implementing the resilience measure.

$$Benefits = D_{Tf} - D_{Tr}$$

$$Benefits = 612{,}820 - 356{,}756$$

$$Benefits = \$256{,}064$$

For the resilience measure to be cost-effective, the net present value of the benefits minus the costs must be greater than 0. So, a resilience measure with an overall cost less than the calculated benefits (Step 16) would be considered cost-effective.

Another way of evaluating the results is to use a benefit-cost ratio. If the ratio of the benefits to the costs is greater than 1, the measure is considered to be cost-effective.

APPENDIX I

Blank Level 1 Worksheet

The following presents a blank Level 1 worksheet.

Level 1: Climate-Adapted Benefit-Cost Analysis

This is an approximate test to see if it would be cost-effective to upgrade assets to the future conditions posed by climate change.

Current Conditions

Step 1. Determine return periods.		
Description	**Variable**	**Value**
Largest return period for which there will be no damage (Design Return Period)	**T_{cnd} (years)**	
Return period associated with an event that would cause moderate but considerable structural damage, or roadway flooding and traffic interruption. This would be the next-highest standard return period to T_{nd}	**T_{cmod} (years)**	
Return period for which damage would be practically maximized	**T_{cmax}(years)**	

Step 2. Determine damages associated with Step 1.		
Total damages associated with T_{cnd}	**D_{cnd} ($)**	
Total damages associated with T_{cmod} (e.g., loss of riprap, short-term road closure, traffic control and road cleanup costs)	**D_{cmod} ($)**	
Total damages associated with T_{cmax} (i.e., failure of the hydraulic structure leading to large structural damage and loss of road service and possibly injuries or fatalities)	**D_{cmax} ($)**	
Present value coefficient for the remaining project useful life (i.e., remaining service life during the period of projected climate change) from Appendix B	**PVC (%)**	

Step 3. Determine current discharge flows associated with Step 2.		
Associate discharges with return period, T_{cnd} under current (no climate change) conditions	**Q_{cnd} (cfs)**	
Associate discharges with return period, T_{cmod} under current (no climate change) conditions	**Q_{cmod} (cfs)**	
Associate discharges with T_{cmax} under current (no climate change) conditions	**Q_{cmax} (cfs)**	

Step 4. Calculate expected annual damages between T_{cnd} and T_{cmod} based on Step 1 and Step 2.

$$D_{acmod} = \frac{D_{cnd}+D_{cmod}}{2} * \left(\frac{1}{T_{cnd}} - \frac{1}{T_{cmod}}\right)$$

Step 5. Calculate expected annual damages between T_{cmod} and T_{cmax} based on Step 1 and Step 2.

$$D_{acmax} = \frac{D_{cmod}+D_{cmax}}{2} * \left(\frac{1}{T_{cmod}} - \frac{1}{T_{cmax}}\right)$$

Step 6. Calculate total Annualized Damages.

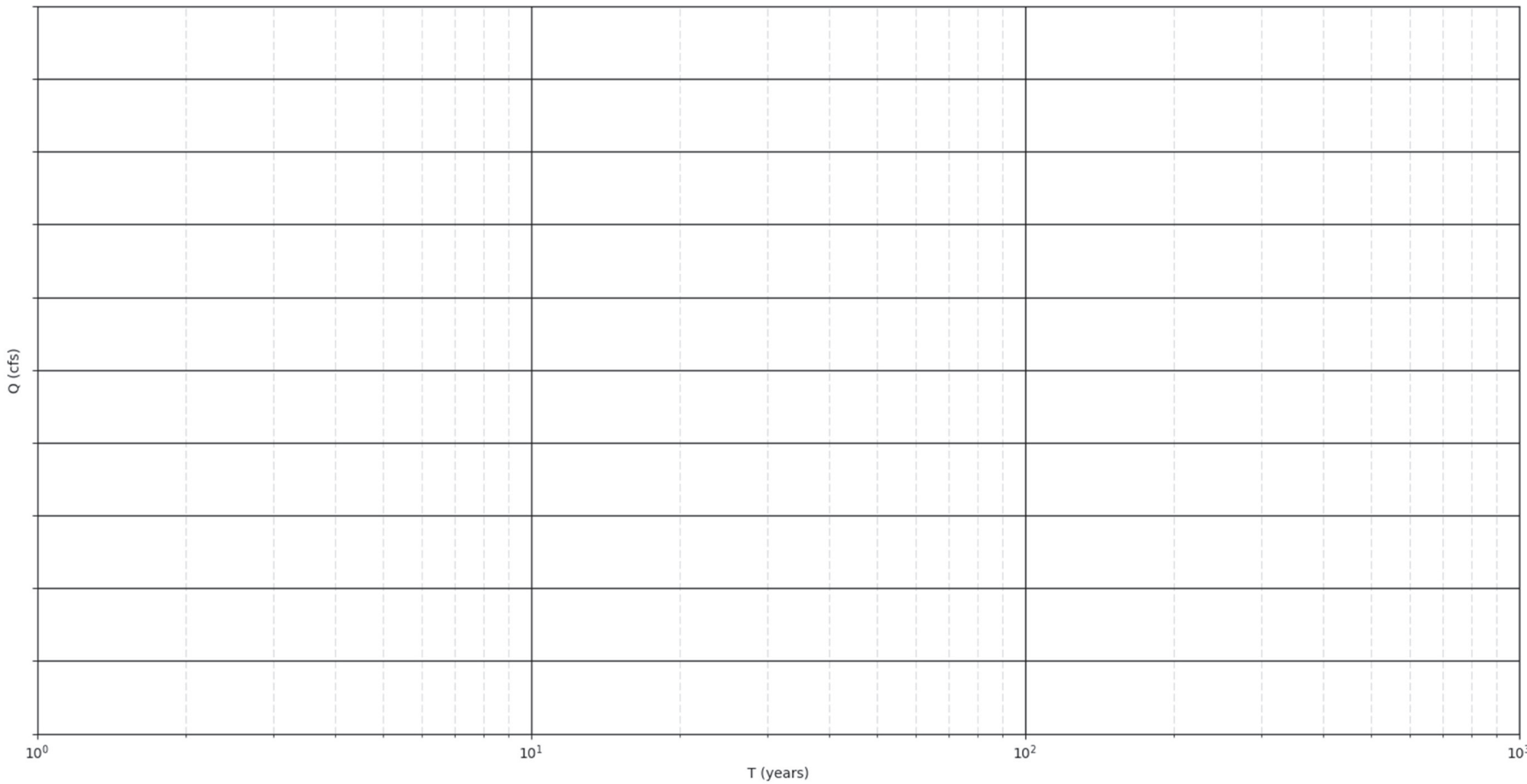
$$D_{ac} = D_{acmod} + D_{acmax}$$

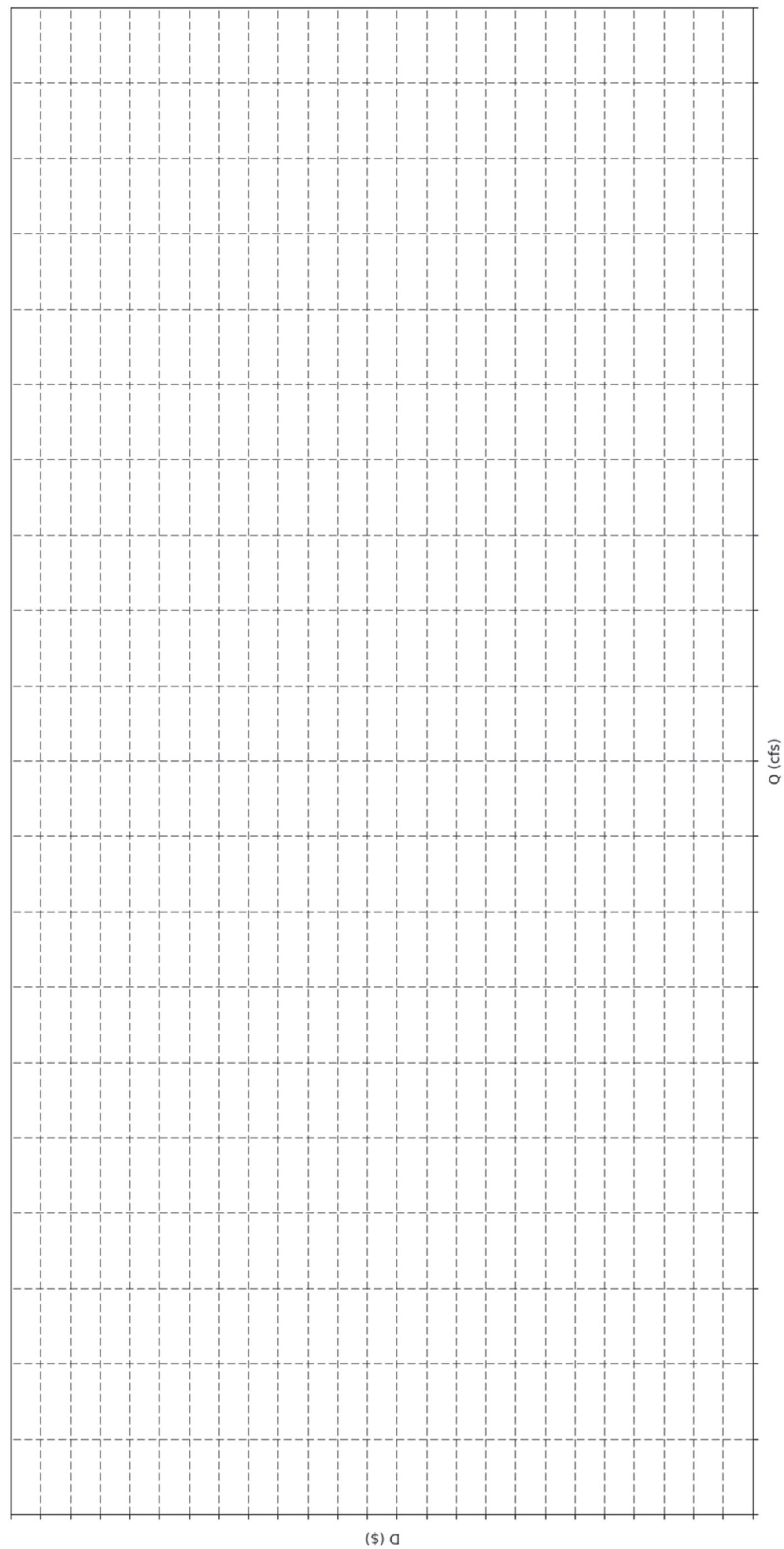
Step 7. Calculate present value of total expected damages under current conditions.
$D_{Tc} = D_{ac} * PVC$ **Note:** PVC can be determined based on Appendix B.

Step 8. Summarize the data for current climate conditions.				
	T_c(years)	D_c($)	Q_c(cfs)	D_{ac}($)
T_{cnd}				
T_{cmod}				
T_{cmax}				
Total annualized damages				

Step 9. Plotting

- Create a graph by plotting the return periods T_{cnd}, T_{cmod}, and T_{cmax} (Step 8) on a logarithmic scale on the *x*-axis against the associated discharges on the *y*-axis.
- Create a second graph by plotting the discharges on the *x*-axis (with a “normal” scale as opposed to logarithmic) and the estimated damages (D) (Step 8) associated with each discharge on the *y*-axis.


Q (cfs)
10^0
10^1
10^2
10^3
T (years)


Q (cfs)
D ($)

Calculate future flows and associated expected damage for future climate conditions. To do this, start by identifying the climate change scenario to be used for analysis (see Chapter 3). For the selected climate scenario, calculate the estimated future discharges for each return period (i.e., return period in which no damage occurs, return period in which moderate damage occurs, and return period in which significant damage occurs). This will result in identifying values for Q_{f1}, Q_{f3}, and Q_{f5}.

Step 10. Calculate the future flows for selected return periods.		
Description	**Variable**	**Value**
Associate discharges with return period, T_{fnd} (i.e., T_{nd}) based on climate change conditions	$\mathbf{Q_{fnd}}$	
Associate discharges with return period, T_{fmod} (i.e., T_{mod}) based on climate change conditions	$\mathbf{Q_{fmod}}$	
Associate discharges with T_{f5} (i.e., T_{fmax}) based on based on climate change conditions	$\mathbf{Q_{fmax}}$	

Step 11. Plotting: Summarize the current and future flows for each return period.			
T_c(years)*	**Q_c (cfs)***	**T_f (years)**	**Q_f (cfs)**

*See Step 8

Plot the future discharges under the selected climate change scenario Q_{fnd}, Q_{fmod}, and Q_{fmax} on the same logarithmic graph as the baseline conditions (see Step 9).

Step 12. Calculate the Future Return period for the selected climate scenario based on Step 11. This provides an estimate of the climate-adjusted return period for the base flow.

$$Log\ T_{fnd} = logT_{fmod} - (Log\ T_{fmod} - Log\ T_{fnd}) * \frac{Q_{fmod} - Q_{cnd}}{Q_{fmod} - Q_{fnd}}$$

and

$$T_{fnd} = 10^{\ Log\ T_{fnd}}$$

T_{fnd} =____*Years*

Step 13. Interpolate the damages (D'_{fnd}) linearly based on revised future discharges (Step 11) using the equations below.

$$D'_{fnd} = D_{cnd} + \frac{(Q_{fnd} - Q_{cnd})}{(Q_{cmod} - Q_{cnd})} * (D_{cmod} - D_{cnd})$$

$D'_{fnd} =$ ____

Step 14. Interpolate the damages (D_{fmod}) linearly based on revised future discharges (Step 11) using the equations below.

$$D_{fmod} = D_{cmod} + \frac{(Q_{fmod} - Q_{cmod})}{(Q_{cmax} - Q_{cmod})} * (D_{cmax} - D_{cmod})$$

$D_{fmod} =$ ____

Step 15. Interpolate the damages (D_{fmax}) linearly based on revised future discharges (Step 11) using the equations below.

$$D_{fmax} = D_{cmax} + \frac{(Q_{fmax} - Q_{cmax})}{Q_{cmax}} * D_{cmax}$$

$D_{fmax} =$ ____

Step 16. Summarize the climate-adjusted values for discharge and damages. Set the future damages (D_{fnd}) corresponding to T_{fnd} to \$0, as this value corresponds to the same discharge as Q_{cnd} (i.e., Q_{cnd}=Q_{fnd}).			
	T_f	D_f (\$)	Q_f (cfs)
T_{fnd}			
T'_{fnd}			
T_{fmod}			
T_{fmax}			

Step 17. Plot the damages against the peak discharges on the same regular graph paper as for the previous figure to develop a curve for climate-adjusted flows.

Step 18. Calculate the annualized damages for climate-adjusted conditions using a similar approach to the previous section, substituting the climate-adjusted values for the current condition values based on Step 16.

$$D'_{afnd} = \frac{D_{fnd}+D'_{fnd}}{2} * (\frac{1}{T_{fnd}} - \frac{1}{T'_{fnd}})$$

D'_{afnd} = ______________________________

Step 19. Calculate the annualized damages for climate-adjusted conditions using a similar approach to the previous section, substituting the climate-adjusted values for the current condition values based on Step 16.

$$D_{afmod} = \frac{D'_{fnd} + D_{fmod}}{2} * (\frac{1}{T'_{fnd}} - \frac{1}{T_{fmod}})$$

D_{afmod} =______________________________

Step 20. Calculate the annualized damages for climate-adjusted conditions using a similar approach to the previous section, substituting the climate-adjusted values for the current condition values based on Step 16.

$$D_{afmax} = \frac{D_{fmod} + D_{fmax}}{2} * (\frac{1}{T_{fmod}} - \frac{1}{T_{fmax}})$$

D_{afmax} = ______________________________

Step 21. Calculate the annualized damages for climate-adjusted conditions using a similar approach to the previous section, substituting the climate-adjusted values for the current condition values.

$D_{af} = D'_{afnd} + D_{afmod} + D_{afmax}$

$D_{af} = \$$____

Step 22. Calculate the annualized damages for climate-adjusted conditions using a similar approach to the previous section, substituting the climate-adjusted values for the current condition values.

$D_{Tf} = D_{af} * PVC$

$D_{Tf} =$ ____

Step 23. Summarize the climate-adjusted values.

	T_f	Q_f (cfs)	Df ($)	D_{af} ($)
T_{fnd}				
T'_{fnd}				
T_{fmod}				
T_{fmax}				

Step 24. Compare the additional damages for the base case with and without climate adjustment using the base case damages calculated in Step 7 and climate-adjusted damages calculated in Step 22.

$\Delta D_T = D_{Tf} - D_{Tc}$

$\Delta D_T =$ ____

This value represents the additional present value of the expected damages from climate change during the asset's remaining useful life. A resilience/mitigation measure aimed at maintaining the current frequency-damage structure (design level) while accounting for climate change must cost less than this value to be cost-effective.

APPENDIX J

Cost-Benefit Analysis Data Sources

HAZUS

Hazus is FEMA's methodology for estimating potential losses from earthquakes, floods, and hurricanes. Potential loss estimates analyzed in Hazus include

- Physical damage to residential and commercial buildings, schools, critical facilities, and infrastructures;
- Economic losses from lost jobs, business interruptions, and repair and reconstruction costs; and
- Social impacts related to sheltering requirements, displaced households, and population exposed to scenario floods, earthquakes, and hurricanes.

Hazus can be downloaded from FEMA's Flood Map Service Center Hazus download page: https://msc.fema.gov/portal/resources/hazus.

USACE Depth-Damage Curves

USACE published a catalog of residential depth-damage functions in 1992 (http://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/92-R-3.pdf). It issued updated guidance on the use of generic depth-damage functions for residential structures with basements in 2003 (https://planning.erdc.dren.mil/toolbox/library/EGMs/egm04-01.pdf). USACE's HEC-FDA software incorporates depth-damage functions to allow users to perform an integrated hydrologic engineering and economic analysis for flood risk management plans (http://www.hec.usace.army.mil/software/hec-fda/).

Other Methodologies and Data Sources

Other methodologies and sources of data are found in Tables J-1 through J-3.

Table J-1. Economic valuation methodologies.

Economic Valuation and Supporting Data	Basis	Source
Value of Statistical Life (VSL)		U.S. DOT, Guidance on Treatment of the Economic Value of a Statistical Life in U.S. Department of Transportation Analyses (2013) https://www.transportation.gov/sites/dot.gov/files/docs/VSL_Guidance_2014.pdf
VSL upper and lower bound as per DOT guidance		Knieser and Viscusi, "Policy Relevant Heterogeneity in the Value of Statistical Life: New Evidence from Panel Data Quantile Regressions" (2009) http://surface.syr.edu/cgi/viewcontent.cgi?article=1047&context=cpr
Value of Injuries	Fraction of VSL	U.S. DOT, Guidance on Treatment of the Economic Value of a Statistical Life in U.S. Department of Transportation Analyses (2013)
Truck Emissions	HC, volatile organic compounds, CO, NO_x, etc.	EPA MOVES
Emissions for eGrid Subregions	NO_x, SO_2, CO_2, CH_4, N_2O	EPA https://www.epa.gov/energy/egrid-summary-tables
Value of Time	Guidance	U.S. DOT Departmental Guidance for Valuation of Travel Time in Economic Analysis
Value of Time	Median Household Income	2009 American Community Survey, 1-year estimates
Value of Time	Median Wage, Employer Costs wages, Employer costs benefits	Bureau of Labor Statistics
Vehicle-Operating Cost		FHWA, AAA report
Inflation Rates	Monthly	U.S. Department of Labor Bureau of Labor Statistics (2013). *Consumer Price Index.* Retrieved from http://www.bls.gov/cpi/

Table J-2. Demographic-transportation data.

Demographic-Transportation Data	Basis	Source
Unemployment Rate	Statewide	Bureau of Labor Statistics
Property Value	Statewide; Property Taxes, Home Value	U.S. Census Bureau; Tax Foundation calculations
Means of Transportation	By Poverty Status/Mode of Transport and Travel Time, All US Metro- and Micropolitan Areas	2013 American Community Survey, 5 Year Average
Population and Population Density	By City	2013 American Community Survey 5-Year Average
Vehicles per Household	By City	2013 American Community Survey 5-Year Average

Table J-3. Representative transportation- and resilience-focused data sources.

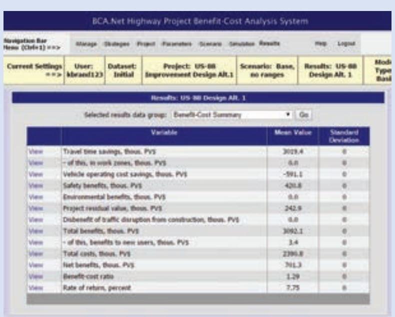
Category	Inputs	Representative Available Data Sources
Transportation-Focused	• Right-of-way acquisition • Rate of depreciation • Rate of deterioration • Project life-cycle costs • Traffic characteristics • Detour cost • Safety statistics • Value of travel time • Price of fuel • Emissions • Fuel tax • Project operations and maintenance costs	• DOT records (e.g., ADT, accidents, maintenance records, passenger travel times, travel characteristics, historical project records, etc.) • Depreciation schedules • Bureau of Labor Statistics • American Petroleum Institute (fuel tax rates, price of fuel) • EPA (emissions) • FEMA BCA Guidance (value of travel time, depreciation) • FHWA website • AASHTO website, portals • TRB publications
Resilience-Focused	• Hazard type • Hazard recurrence interval • Infrastructure criticality to network • Proposed mitigation • Loss of function cost • Estimated damages • Climate scenarios	• State and local hazard mitigation plans (hazard types, recurrence interval) • FEMA BCA Guidance (recurrence intervals) • FIRMs (recurrence intervals) • IPCC (climate change scenarios) • FHWA website • AASHTO website, portals • TRB publications • DOT Vulnerability Assessment (criticality) • DOT Asset Management Plan (criticality) • *State Climatologist* (climate data) • Universities (climate data)
Common to both	• Discount rate • Infrastructure facility type and design characteristics • Planned project construction start date • Planned project construction duration	• OMB Circular A-94 • Project design documents • Project construction schedule • FHWA Primer GASB 34 • FHWA Financial Planning for Transportation Asset Management: An Overview

APPENDIX K

Cost-Benefit Analysis Tools

Tools evaluated over the course of this project provided some useful insights into components of a comprehensive methodology for comparing adaptation alternatives for extreme weather and climate change using CBA. Tables K-1 through K-4 provide detailed summaries of some of these tools. More comprehensive lists of tools are summarized in Tables K-5 and K-6.

Table K-1. Cost analysis tools for infrastructure investment in the transportation sector.

Tool Name/Screenshot	Details
BCA.net 	**BCA.net** compares highway management and improvement scenarios and provides sensitivity analysis, allowing users to explore how benefits change in response to inputs. Produces estimates for total benefits, total costs, net benefit, BCR, and rate of return.
	Applicability: Web-based (reducing potential IT security issues), tabular inputs and outputs, data inputs are commonly available design and performance statistics, compares multiple strategies across varying scenarios, values a variety of benefits.
	Usability Challenges: Confined to highway projects (resurfacing, widening, adding lanes, reversible lanes, and combinations thereof), project level only.
Surface Transportation Efficiency Analysis Model (STEAM)	**STEAM** assesses multimodal infrastructure alternatives as well as policy alternatives. Produces estimates for net present worth and BCR.
	Applicability: Estimates infrastructure and operating costs, compatible with typical travel-demand management software, has a strong framework considering livability and accessibility, regional-level analysis. Considers • Automobiles/carpool, • Truck, • Local bus/express bus, • Light rail, and • Heavy rail.

(continued on next page)

Table K-1. (Continued).

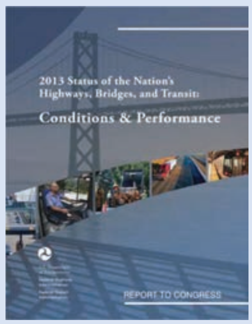
Tool Name/Screenshot	Details
	Usability Challenges: Desktop-based application built in the late 1990s and last versioned in the early 2000s; somewhat cumbersome manual input required for multiple alternatives analyses.
National Bridge Investment Analysis System (NBIAS) 	**NBIAS** is a national-level tool predicting the conditions and performance of the bridges in the National Bridge Inventory. **Related:** HERS and HERS-ST, which focus on roadways (similar user cost parameters).
	Applicability: Provides system-level (in this case, national) benefit-cost analyses on maintenance, repair, and rehabilitation work to be performed; condition deterioration probability curves vary based on (stationary) climate zones; produces useful enterprise-level statistics on funding needs, backlog, structural deficiencies, and user benefits; uses readily available NBI data (and will incorporate National Bridge Element Data to comply with MAP-21).
	Usability Challenges: Single-asset, outputs may be of limited use at the project level, conditions and performance alternatives analysis is supported but analysis of impact of various types of replacements is not supported (e.g., “replacement” recommendation is implicitly replace-in-kind).
RealCost v2.5 	**RealCost v2.5** is a desktop-based, project-level life-cycle analysis tool with alternatives analysis for highway projects **Related:** Bridge-specific life-cycle analysis: Pontis (older but still in use); NIST’s BLCC; FHWA’s BLCCA.
	Applicability: Indicates both agency cost and user costs for various alternatives, includes costs and performance characteristics related to work zones; is intended to support alternatives analysis for up to six different structural designs.
	Usability Challenges: Single-asset roadway geometry must be identical for all alternatives (important for LCCA best practices but problematic when adaptation alternatives may include reconfiguring or relocating roadways), desktop-based Excel with VBA likely to cause IT security conflicts; current version appears incompatible with Excel 2013.

Table K-1. (Continued).

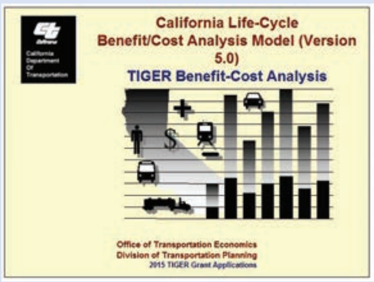
Tool Name/Screenshot	Details
Caltrans California Life-Cycle Benefit/ Cost Analysis Model 	**Caltrans California Life Cycle Benefit/Cost Analysis Model** analyzes capacity-expansion projects for several modes. Estimates NPV, BCR, rate of return, and project payback period.
	Applicability: Handles road, rail, transit, and combinations thereof; includes a module compatible with federal grant requirements (TIGER); has evolved to support project-, network-, and corridor-level analyses. The current build (v5.0) also supports analysis of operational improvements and transportation management systems.
	Usability Challenges: Model default values are California-centric; asset life cycle is fixed at 20 years (not suitable for bridges or other long–life cycle structures); can be unclear when project-, corridor-, or network-level analysis is needed; desktop-based Excel with macros likely to cause IT security conflicts.

Table K-2. Weather-related CBA tools for the transportation sector.

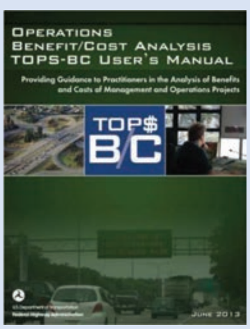
Tool Name/Screenshot	Details
TOPS-BC 	**TOPS-BC: Tool for Operations Benefit/Cost (2013)**, a sketch-level decision support tool developed to use the FHWA's guidance on benefit-cost. **Related:** Operations Benefit/Cost Analysis Desk Reference; Road Weather Management Cost Benefit Analysis Compendium.
	Applicability: Establishes the benefits of road weather management with respect to operational considerations (travel time, travel time reliability, crashes).
	Usability Challenges: Limited to roadway assets. Existing case studies are not typically multi-hazard (i.e., winter weather dominates). Does not consider changing climate.
Clear Roads BC Toolkit 	**Clear Roads BC Toolkit (updated 2013):** Estimates the benefits and costs of practices, equipment, and operations related to winter weather.
	Applicability: Establishes the benefits of winter maintenance activities.
	Usability Challenges: Limited to roadway assets. Focuses solely on winter weather. Does not consider changing climate.

Table K-3. Hazard mitigation CBA tools relevant to the transportation sector.

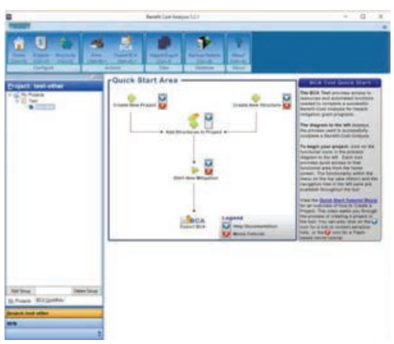
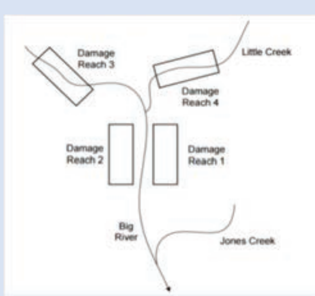
Tool Name/Screenshot	Details
CAPTool 	**CAPTool** is a spreadsheet tool designed to capture capital and operations costs for transportation hazard mitigation activities.
	Applicability: Considers extreme weather; strategies organized by asset, mode, or hazard; multimodal and all-hazards; alternatives analysis; analysis based on agency-defined risk thresholds; provides enterprise-level and asset-specific summary; considers capital and operating costs.
	Usability Challenges: Provides cost of countermeasure but no quantification of benefit (framework is "impacts mitigated" rather than losses or damages avoided); does not distinguish type of extreme weather; desktop-based Excel with macros likely to cause IT security conflicts.
FEMA BCA Tool 	The multi-hazard **FEMA BCA Tool** allows analysis of multiple assets for a single mitigation project; support for analyzing impacts of sea level rise, and some consideration of social/environmental benefits as well as traditional benefit categories (avoided structure damage, contents damage, and displacement/service losses for utilities, roads, and bridges).
	Applicability: Multi-hazard, allows analysis of multiple assets for a single mitigation project, support for analyzing impacts of sea level rise, some consideration of social and environmental benefits. **Related:** HAZUS-MH, which has fragility curves for building structures that can develop loss estimates for earthquake, high wind, and floods, which may be useful as a CBA input.
	Usability Challenges: Cumbersome to run multiple alternatives analyses or hazard scenarios; cannot easily compare alternatives across hazards (changing climate is characterized by multiple changes to design-relevant characteristics simultaneously); assumes stationary recurrence intervals (with changing climate, recurrence intervals shift over time, i.e., non-stationarity); does not offer comparison against a "no-build" scenario; benefits are solely damages avoided (not multi-objective).
USACE Flood Damage Reduction Analysis (HEC-FDA) 	**HEC-FDA** is a tool to assess the effectiveness of a project from both a risk perspective and an economic perspective.
	Applicability: Computes both hazard risk reduction and economic aspects of alternatives.
	Usability Challenges: Single hazard, not developed for transportation sector (roads have to be treated as a "pseudo-structure"); project performance is assessed over return period and not asset life cycle; stationary return periods; output is damages (thus damages avoided are the only benefit that can be computed).

Table K-3. (Continued).

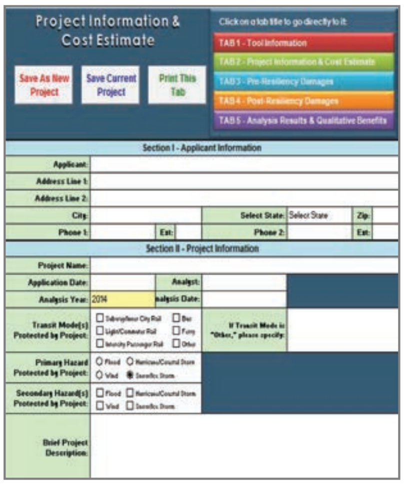
Tool Name/Screenshot	Details
FTA HMCE Tool 	The **FTA HMCE Tool** is designed for transit resilience projects with FTA hazard mitigation grant programs. Provides CBAs for floods, hurricanes, and coastal storms using a methodology based on the FEMA BCA Tool damage-frequency assessment option. Provides benefits, costs, and BCR as well as inputs to include other benefits such as lost transit revenue.
	Applicability: Simplified tool that allows analysis of a single transit mitigation project, and includes a supplemental calculator to adjust coastal flood recurrence internals to account for sea level rise impacts and detailed considerations of avoided physical damages as well as socioeconomic impacts of lost transit service.
	Usability Challenges: Cumbersome to run multiple alternatives analyses or hazard scenarios; cannot easily compare alternatives across hazards; assumes stationary recurrence intervals (with changing climate, recurrence intervals shift over time, i.e., non-stationarity); does not automatically offer comparison against a "no-build" scenario; benefits are solely damages avoided (not multi-objective); current version has limited geography (East Coast from New England to Mid-Atlantic states)

Table K-4. Climate-resilience CBA tools relevant to the transportation sector.

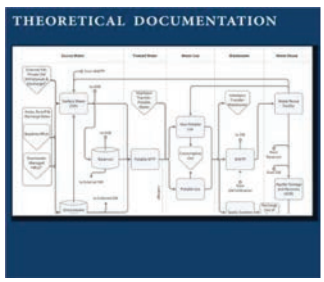
Tool Name/Screenshot	Details
NOAA Port Tomorrow Resilience Planning Tool Prototype 	**NOAA Port Tomorrow Resilience Planning Tool Prototype**. Although no longer maintained, this tool compiled resiliency summaries and checklists for ports.
	Applicability: Useful vulnerability characteristics, such as indicating whether ports were NOAA storm- or tsunami-ready, and depicting high-traffic navigation areas as well as hazardous materials incident statistics. Summaries of livability and economic development activities.
	Usability Challenges: Not cross-asset, not quantitative, does not explicitly account for changing climate, no longer maintained.
Watershed Management Optimization Support Tool 	The **Watershed Management Optimization Support Tool** was designed by EPA and developed principally for water resources managers and planners in coastal locales.
	Applicability: Operations-focused; support for low-impact development (LID) and green infrastructure stormwater best management practices; incorporates metrics for cost-effectiveness, environmental aspects, and sustainability; considers a range of climate scenarios.
	Usability Challenges: Focuses solely on water resources and land use management, local/single watershed only.
U.S. Climate Resiliency Toolkit Beach-*fx* 	**U.S. Climate Resiliency Toolkit Beach-*fx*** is a USACE tool evaluating performance, cost, and benefits of activities to mitigate erosion, inundation, and wave damage.
	Applicability: Considers various damage categories (erosion, inundation, and wave impact); evaluates alternatives; considers economic consequences as well as losses from direct damage; considers local storm record, considers effect of local morphology on storm impact.
	Usability Challenges: Coastal resources only, focus on assets or programs with a primary function of protection (nourishment, shoreline structures), does not consider changing climate.

Table K-4. (Continued).

Tool Name/Screenshot	Details
COAST 	**COAST** is a proprietary but freely available tool for comparing benefits and costs of proposed adaptation alternatives in the coastal environment and has been used successfully by MaineDOT.
	Applicability: Geospatially enabled to capture the extent of the hazard being examined; evaluates alternatives; computes losses over the life cycle of infrastructure (cumulative losses); losses evaluated include direct losses as well as impacts to economic output, displaced persons, and impacts to cultural and natural resources.
	Usability Challenges: Exclusively considers coastal impacts and adaptations, limited to examining one scenario at a time, use of the software may require significant support from the development team.

The tools listed in Table K-5 are in the public domain, commonly used at state transportation agencies, quantitative, developed, and in use in the past 15–20 years. Some DOTs may lack an all-assets asset catalogue. For example, bridge culverts and non-bridge culverts may be kept in separate databases, such as Pontis and Maximo, respectively. Links are either to tool documentation (particularly in the case of older or proprietary tools that do not have public downloads available), or tool download locations, where available. An un-linked tool name indicates that current documentation and downloads are not available.

Based on this assessment, it appears that most hazard mitigation tools (Table K-6) account for impacts to the capital budget, but not necessarily the operating budget. CAPTool is an exception, providing estimates for both.

Table K-5. Capital-improvement and operations tools (Venner, 2014).

Tool	Developed By	Infrastructure/ Operational Focus	Considers	Asset Management Level (asset/corridor/network)	Project/Program Level
AASHTO Red Book	AASHTO	Infrastructure	Highway (Operational)	Asset	Project
AASHTOWare Project (was TRNS*PORT)	AASHTO	Operations	Construction	Asset	Project
AssetManager NT	NCHRP	Infrastructure	Highway; Bridge	Network	Program
AssetManager PT	NCHRP	Infrastructure	Highway; Bridge	Network	Program
BCAnalysis	Florida DOT	Both	Highway	Asset	Project
BCA.Net	FHWA	Infrastructure	Highway	Asset	Project
BLCCA	NCHRP	Infrastructure	Bridge	Asset	Project
Cal-B/C	Caltrans	Infrastructure	Highway; Transit	Asset/Corridor/Network	Project; Program
CIMS (Culvert Information Management System)	NJDOT	Infrastructure	Culvert	Asset/Network	Program
Clear Roads BC Toolkit	Clear Roads Consortium	Operations	Highway	Network	Program
COMMUTER	EPA	Operations	Highway (Emissions)	Network	Program
DIETT	NCHRP	Operations	Bridges and Tunnels	Network	Program
EMFITS	NYSDOT	Both	Intelligent Transportation System (ITS)	Network	Program
FITSEval	Florida DOT	Both	ITS	Network	Program
HDM-4	HDMGlobal/ World Bank	Infrastructure	Highway	Asset/Corridor/Network	Project; Program
HERS-ST	FHWA	Infrastructure	Highway	Network	Program
IDAS	FHWA	Both	ITS	Network	Program
IMPACTS	FHWA	Infrastructure	Multimodal	Corridor	Program
Interactive Interchange Management System	SCDOT	Infrastructure	Highway; Bridge	Network	Program
MBCA	TREDIS	Infrastructure	Multimodal	Asset	Project
MicroBENCOST	NCHRP	Infrastructure	Highway; Safety	Corridor	Project
MOOS Bridge Level	NCHRP	Infrastructure	Bridge	Asset	Project
MOOS Network Level	NCHRP	Infrastructure	Bridge	Network	Program
NBIAS	FHWA	Infrastructure	Bridge	Network	Program
PONTIS (now AASHTOWare Bridge Management)	AASHTO	Infrastructure	Bridge	Network	Project; Program
REALCOST	FHWA	Infrastructure	Highway	Asset	Project
Smart Roadside	AASHTO	Infrastructure	ITS	Asset	Project
SCRITS	FHWA	Both	ITS	Network	Program
STEAM	FHWA	Infrastructure	Multimodal	Corridor	Project
StratBENCOST	NCHRP	Infrastructure	Highway	Asset/Network	Project
TIM-BC	FHWA	Operations	Highway (Incident Management)	Network	Program
TOPS-BC	FHWA	Operations	Highway	Network	Program
TransValU	FDOT District Five	Both	Multimodal	Corridor	Project; Program
TRIMMS	CUTR, University of South Florida	Operations	Highway	Network	Program

Table K-6. Hazard mitigation, CCA, resilience, and sustainability tools.

Tool	Developed By	Infrastructure/ Operational Focus	Framework Type	Developed for (or including) Transportation Sector (Y/N)	Considers	Geographic Scale
Beach-*fx*	USACE	Infrastructure	Resiliency	No	Protective structures; coastal hazards	Sub-state (coastal)
Blowing Snow Control Tools	MnDOT and UM Extension	Operations	Resiliency	Yes	Snow fences	Sub-state
Business Case Evaluator—Transit Module	Impact Infrastructure	Infrastructure	Sustainability	Yes	Sustainability of new or retrofitted transit infrastructure	Local
CAPTool	FHWA	Infrastructure	Hazard Mitigation	Yes	Cross-asset; examines multiple assets simultaneously; multi-hazard	Regional, state, or local
COAST	Blue Marble Geographics	Infrastructure	Resiliency	No	Life-cycle benefit-cost analysis for infrastructure alternatives, including no-build. Cumulative loss avoidance over various climate scenarios.	Sub-state (coastal)
FEMA BCA Tool	FEMA	Infrastructure	Hazard Mitigation	No	Multi-hazard; potentially cross-asset	Sub-state
FTA HMCE Tool	FTA	Infrastructure	Resiliency	Yes	Multi-hazard; coastal flood recurrence/SLR, physical damages; lost transit service	Regional, state, or local
HEC-FDA	USACE	Infrastructure	Hazard Mitigation	No	Coastal hazards; examines multiple assets simultaneously	Sub-state (coastal)
InVEST	Natural Capital Project	Operations	Sustainability	No	Ecosystem services values (e.g., water regulation, moderation of extreme events, air quality, climate stability)	Sub-state
IPSS	Resilient Analytics	Infrastructure	Resiliency	Yes	Evaluate investment options for various climate scenarios and build dates throughout an infrastructure network	Regional, state, or local
iTree	USDAA Forest Service	Operations	Sustainability	No (except iTree Streets)	Ecosystem services values for trees and forests (water quality, air quality, carbon sinks)	Local
NIST EDGe$	National Institute for Standards and Technology	Infrastructure	Resiliency	Yes	Benefit-cost analysis of community resilience adaptation strategies	Regional, state, or local
PRISM	WSP	Operations	Sustainability	Yes	Triple bottom-line (sustainability) valuation of transportation projects	Regional, state, or local
SERVES	Earth Economics	Operations	Sustainability	No	Ecosystem services values (e.g., water regulation, moderation of extreme events, air quality, climate stability)	NA (prototype)
Watershed Management Optimization Support Tool	EPA	Operations	Resiliency	No	Watershed management strategies; multiple climate scenarios and time frames	Sub-state (coastal)

APPENDIX L

Existing Frameworks Related to the Cost-Benefit Analysis Process

During the course of research for the project, several existing frameworks were identified that are related to and support completing CBAs for climate adaptation. These frameworks are summarized in Table L-1.

Table L-1. Vulnerability assessments and transportation asset management plans contain many of the prerequisites for the climate-resilience CBA process.

Frameworks	Objective	Key Information
FHWA Vulnerability Assessments (2012)	Understanding the transportation system's vulnerability to climate change	• Asset type and characteristics • Asset criticality • Asset vulnerability to key climate variables • Risk (based on vulnerability and likelihood of impact) • Adaptation options • Ranked priorities
MAP-21—Compliant Transportation Asset Management Plans (TAMP) (2013)	Enabling sustainable asset stewardship and investment	• Asset listing and conditions (MAP-21 requires, at minimum, pavement and bridges) • Asset management objectives and measures • Performance gaps • Life-cycle cost and risk analysis • Financial plan • Investment strategies (FHWA, 2016)
TAMP for Extreme Weather and Adaptation (Meyer and Flood, 2015)	Building resilience to extreme weather and climate change into transportation assets	• Record of asset performance and damage during previous extreme events • Frequency and type of extreme weather events that have been experienced • Projected changes in extreme events and expected impact to agency objectives, asset condition, performance, maintenance, and life-cycle management • Relative ranking of vulnerability by asset category • Identification of "too important to fail" and "repetitive loss" assets • Reconstruction and recovery funding needs and mechanisms

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Acronyms

ADT	average daily traffic
BCA	benefit-cost analysis
BCR	benefit-cost ratio
BUILD	Better Utilizing Investments to Leverage Development
CBA	cost-benefit analysis
cfs	cubic feet per second
CH_4	methane
CMIP	Coupled Model Intercomparison Project
CO_2	carbon dioxide
CREAT	Climate Resilience Evaluation and Awareness Tool
DOT	Department of transportation
EIA	Economic impact analysis
ER	Emergency Relief
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Study
FY	fiscal year
GCM	general circulation model
GHG	greenhouse gas
HEC	Hydraulic Engineering Circular
IDF	intensity-duration-frequency
IRR	internal rate of return
ITS	intelligent transportation system
IWG	Interagency Working Group
LCCA	life-cycle cost analysis
MnDOT	Minnesota Department of Transportation
MOVES	Motor Vehicle Emission Simulator
N_2O	nitrous oxide
NO_x	nitrogen oxides
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NPV	net present value
O&M	operations and maintenance
OMB	Office of Management and Budget
P3	public-private partnership
ppm	parts per million
PV	present value
PVC	present value coefficient

RCP	representative concentration pathway
RI	recurrence interval
ROI	return on investment
S-NPV	sustainable net present value
S-ROI	sustainable return on investment
SC-CO_2	social cost of carbon
SLR	sea level rise
SO_x	sulfur dioxides
SRES	Special Report on Emissions Scenarios
STIP	state transportation improvement plan
SWMM-CAT	Stormwater Management Model Climate Adjustment Tool
TAMP	transportation asset management plan
TBL	triple bottom line
TIGER	Transportation Investment Generating Economic Recovery
USGS	United States Geological Survey
VPD	vehicles per day
VSL	value of statistical life

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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