Project No. **20-44(23)**

Pilot Test of Climate Change Design Practices Guide for Hydrology and Hydraulics

Contractor's Report: Case Studies and Lessons Learned

Prepared for

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Executive Summary

Inland and coastal flooding incidences are projected to increase across the country due to climate change, which might need to be factored into design flood calculations, especially when infrastructure has a long service life. However, typical engineering procedures don't provide guidance to incorporate information about future climate change into design. To address this challenge, in 2019, the National Cooperative Highway Research Program (NCHRP) released a set of provisional guidelines under project 15-61 called "Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure" (referred to as the Guide). The Guide was developed to help DOTs and other stakeholders consider the potential effects of climate change in the hydrologic and hydraulic design of roads, culverts, bridges, and other transportation assets.

To evaluate and improve the Guide, the NCHRP under NCHRP 20-44(23) contracted Dewberry Engineers, Inc. to coordinate a group of state DOTs to apply the Guide to existing and planned infrastructure projects (hereafter called the pilot projects). In 2021 a total of nine coastal and inland pilot projects were initiated and completed by DOTs and their contractors in Arizona, Colorado, Florida, Iowa, Maine, Maryland, North Carolina, and Oregon. Dewberry and their subcontractors worked closely with the pilot projects to understand how they were using the Guide and how the Guide could be improved in future iterations.

This report presents case studies that summarize each pilot project and key lessons learned. The case study format is standardized but also tailored to account for the diversity of pilot scope and content. Following are some highlights and key takeaways described in the report:

- The pilot projects analyzed the projected impact of climate change due to increased flooding and scour on a variety of transportation infrastructure including highways, bridges, and culverts at both inland and coastal locations.
- The inland pilot projects followed the 10-step procedure in the Guide to calculate the projected effect of climate change on extreme precipitation, which ranged from roughly +6% to +30% for different scenarios of interest.
- The inland pilot projects used the Guide to estimate how the projected increases in extreme precipitation would affect the design discharge. Using approaches in the Guide, such as regression equation analysis and rainfall/runoff modeling, the projected increase in the design discharge for different scenarios of interest was as high as +33%.
- The coastal pilot projects used methods in the Guide and more advanced probabilistic methods to estimate projected sea level rise and its impact on coastal storm surge and wave action at project locations.
- The pilot projects found that the projected impact of climate change on design and performance over the lifetime of infrastructure varied across projects, from negligible to substantial.

The last section of the report summarizes key lessons learned for users of the Guide, including staffing requirements, the consistency of results, and the potential impacts on the overall design process. The report appendix contains project reports for five of the nine projects with additional details on the project sites, methods, and conclusions.

Chapter 1

Introduction

High-water events are a major hazard for bridges and other transportation infrastructure in the managed floodplain. Transportation engineers typically design infrastructure to withstand flooding up to a "design event," such as the 1% annual exceedance probability (AEP) flood, which is calculated using historical data on a regional basis. However, inland and coastal flooding incidences are projected to increase across the country due to climate change, which might need to be factored into the design flood calculation, especially when infrastructure has a long service life. Unfortunately, engineering guidance doesn't typically provide methods to incorporate information about future climate change into design calculations.

To address this challenge, in 2019, the National Cooperative Highway Research Program (NCHRP) released a set of provisional guidelines under project 15-61 called "Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure" (referred to as the Guide). The Guide was developed to help DOTs and other stakeholders consider the potential effects of climate change in the hydrologic and hydraulic (H&H) design of roads, culverts, bridges, and other transportation assets.

To evaluate and improve the Guide, the NCHRP under NCHRP 20-44(23) contracted Dewberry Engineers, Inc. and their subcontracts, AEM Corporation (hereafter called the Study Team). The Study Team coordinated a group of state DOTs to apply the Guide to existing and planned infrastructure projects (the pilot projects). In 2021 a total of nine coastal and inland pilot projects were initiated and completed by DOTs in Arizona, Colorado, Florida, Iowa, Maine, Maryland, North Carolina, and Oregon. The Study Team worked closely with the pilot projects to understand how they were using the Guide and how they would like them to be improved in future iterations.

1.1 Report Overview

The objective of this Case Studies and Lessons Learned report is to help DOTs implement the Guide by presenting the experience of the nine pilot projects and to share the key lessons learned. The report presents each pilot project as a short case study that summarizes the project site, the pilot objectives, the projected changes in climate, the projected changes in project hydrology and other conditions, and any potential impacts to project resilience and design. The case study format is standardized but also tailored to account for the diversity of pilot scope and content. The last section of the report summarizes key lessons learned with practical considerations for project planners and designers, such as staffing requirements for implementing the Guide, the consistency of the results, and the potential impacts on the overall design process. The report appendix contains project reports for five of the nine projects with more details on the project sites, methods, and conclusions.

1.2 Companion Document: Proposed Revisions

As part of NCHRP 20-44(23), a companion document has been produced with a summary of the revisions and improvements that the pilot projects recommended for future versions of the Guide. The participating DOTs had many ideas to improve the Guide for future users. These ideas have been assembled and summarized in this document, “Proposed Revisions to NCHRP 15-61,” also referred to as the Guide Revisions Report, which serves as a foundational resource for future revisions to the Guide. It provides a complete list of all the changes and improvements proposed by the pilot DOTs and their implementing partners (e.g., consultants) while also highlighting the most emphatic and frequent recommendations. In addition, this document identifies approaches to implement the proposed revisions in future iterations. The approaches range from concept-level suggestions to specific inline textual edits.

Chapter 2

Design Guidelines Overview

To fully appreciate the descriptions of the case studies and lessons learned that follow, it is important to have a contextual understanding of the original Guide. Following is a very brief overview of the Guide contents. The reader is encouraged to review the full text of the Guide at https://onlinepubs.trb.org/Onlinepubs/nchrp/docs/NCHRP1561DesignPracticesGuide_rev.pdf.

In 2016 the NCHRP launched project 15-61 called "Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure." The research project's objective was "to develop a design guide of national scope to provide hydraulic engineers with the tools needed to amend practice to account for climate change." Principal Investigator Roger Kilgore led a team of researchers to complete the first provisional version of the Guide in 2019 called "Design Practices Guide for Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure."

The 154-page Guide is split into three parts. Part I provides an overview of the scope and use of the Guide. It introduces decision making frameworks for considering climate change in hydrologic and coastal engineering applications. The frameworks recognize that not all projects and studies require the same rigor and provides a method to determine the appropriate level of analysis in any given project.

Part II addresses inland hydrology, including the analysis of precipitation, runoff (discharge), infiltration, evaporation, soil moisture, groundwater, temperature, and other factors affecting runoff in a watershed. The chapters in Part II provide guidance on selecting and using information from Global Climate Models (GCMs) and overview basic tools for incorporating climate change into hydrologic analysis and design. Part II also describes specific methods to analyze trends in historical discharges in gauged watersheds; estimate projected precipitation for use in rainfall/runoff models in ungauged watersheds; and estimate future discharge using regression techniques, index approaches, and continuous simulation models under projected precipitation and temperature.

Part III addresses coastal applications with a focus on sea level rise and storm-related coastal hazards. The chapters provide general guidance for selecting sea level rise for analysis and design, as well as guidance on combining coastal hazards, primarily water levels and waves, with available climate change information.

Chapter 3

Pilot Projects Overview

In 2021-2022, eight state DOTs conducted nine pilot projects using the Guide to incorporate climate change information into the hydrologic and hydraulic design of transportation infrastructure. The Study Team supported the identification and development of the pilot projects and worked closely with the pilots to provide technical support and solicit feedback on the Guide. This chapter describes this process of pilot project identification, implementation, and feedback solicitation to provide the reader with context on how the pilot projects were implemented and documented.

3.1 Pilot Project Identification

In 2020, the Study Team initiated a national search for state DOTs interested in implementing a pilot project. The Study Team identified eight interested DOTs with a diverse set of interesting projects (see Figure 1).

It was important to verify that the eight DOTs would use and evaluate the many different approaches described in the Guide. The Study Team identified 17 components in the Guide that could be tested by the DOTs, ranging from the selection of climate scenarios (section 3.1) to the projection of coastal design specifications using hydrodynamical modeling (section 12.4). NCHRP Project 20-44(23) aimed to test as many of these components as possible. Table 1 shows a matrix with the Study Team's best estimate of which components would be tested by the DOT projects at the onset of project. The matrix shows that the nine proposed projects by the eight DOTs would collectively test all 17 components. Most of the components (at least 12 out of 17) would be tested by two or more DOTs.

Table 1. Summary matrix showing the alignment between the Guide components and projects proposed by each state DOT for testing, based on the best available information at the start of the pilots.

	Components of the Guide	Ref Ch.[1]	AZ	CO	FL	IA	MD	ME	NC	OR
Climate	Select climate scenarios	3.1	●	●	●	●	●	●	●	●
	Select climate projections	3.2	●	●	●	●	●	●	●	●
	Select climate models	3.2	●	●	●	●	●	●	●	●
	Calculate climate change index	4.4	◐	◐	◐	◐	◐	◐	●	○

Table continued on next page.

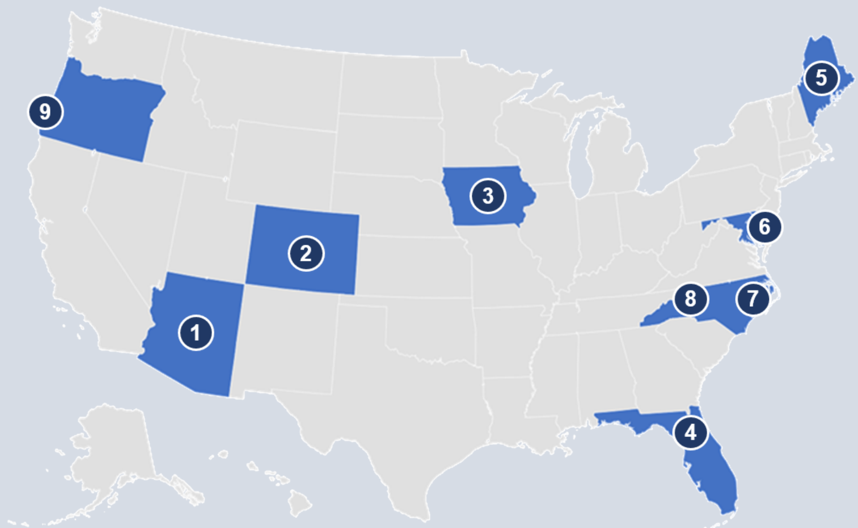
Table 1 (cont.). Summary matrix showing the alignment between the Guide components and projects proposed by each state DOT for testing, based on the best available information at the start of the pilots.

	Components of the Guide	Ref Ch.[1]	AZ	CO	FL	IA	MD	ME	NC	OR
Inland H&H	Select level of inland analysis	4.1	●	●	●	●	●	●	●	●
	Estimate design discharge based on historic trends	5	◐	●	○	◐	◐	○	◐	○
	Estimate design discharge based on rainfall-runoff model	6	○	●	○	●	○	●	●	○
	Estimate design discharge with USGS regression equations	7	●	●	○	○	○	●	○	●
	Estimate discharge based on index approach	8	●	●	○	○	●	●	○	○
	Estimate continuous discharge time series under projected climate conditions	9	○	◐	○	○	○	○	●	○
Coastal Applications	Select level of coastal analysis	10	○	○	●	○	○	○	●	●
	Estimate SLR under climate change using site-specific studies	11.2	○	○	●	○	○	○	●	●
	Estimate SLR under climate change using gridded SLR data	11.2	○	○	●	○	○	○	●	○
	Estimate SLR under climate change using United States Geological Survey (USGS) calculator	11.2	○	○	●	○	○	○	●	●
	Estimate SLR under climate change using National Oceanic and Atmospheric Administration (NOAA) tide station data	11.2	○	○	●	○	○	○	●	●
	Project coastal specifications using design equations	12.1-12.3	○	○	●	○	○	○	●	
	Project coastal specifications using hydrodynamical modeling	12.4	○	○	●	○	○	○	●	

●: Component was likely to be tested; ◐: potentially tested; ○: unlikely to be tested

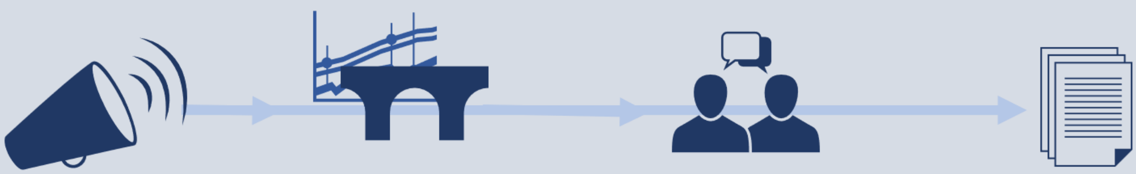
[1]Ref Ch. Is the reference chapter in the Guide

State DOTs Participating in Pilot Projects



1. Arizona
2. Colorado
3. Iowa
4. Florida
5. Maine
6. Maryland
7. North Carolina (Coastal)
8. North Carolina (Inland)
9. Oregon

Guide Revisions Report Development Process



Pilot Project Initiation

Open invitation to state DOTs interested in implementing a pilot project. States self-identified based on interest and the pilot's ability to test a wide range of topics in the Guide.

Pilot Projects

State DOTs conducted proposed pilots. The Study Team provided technical support and documented progress through monthly LOE surveys.

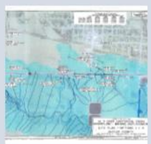
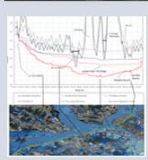
Pilot Project Close Out

The Study Team solicited feedback from the state DOTs on the Design Guidelines primarily through post-pilot interviews, a two-day workshop featuring project presentations and discussion of findings, and final project reports (where available).

Guide Revisions Report & Case Studies Reference

The pilot projects and feedback generated 54 unique proposed revisions to the Design Guidelines detailed in the Guide Revisions Report and informed the development of a Case Studies Reference to support current implementation efforts.

Figure 1 (this page and next page). Location of nine pilot projects with description of pilot process.

State DOT			Design Guidelines Climate Change Pilot Project
1		**Arizona**	Bridge renovation project over a large river corridor considering precipitation and temperature effects
2		**Colorado**	Bridge scour evaluation including historic gauge trend analysis
3		**Iowa**	Level of flood protection evaluation at two bridge locations
4		**Florida**	Retrospective analysis of sea-level rise and wave action on tidally-influenced, two-lane bridge redesign
5		**Maine**	New highway project with numerous stormwater cross-culverts and larger culverts carrying perennial streams
6		**Maryland**	Roadway improvement project including bridge widening, stream realignment, culvert upgrades, and stormwater facilities
7		**North Carolina (Coastal)**	Flood frequency analysis including nuisance flooding at coastal highway bridge.
8		**North Carolina (Inland)**	Hydraulic performance assessment of I-95 corridor to future rainfall projections.
9		**Oregon**	Retrospective pilot on bridge replacement on complex site

3.2 Pilot Project Feedback

The Study Team worked with DOTs to provide training on the Guide as well as solicit comments and proposed revisions to the Guide. Feedback was collected from three primary sources:

- Level of effort surveys: The pilot teams completed a monthly online survey to share progress reports, pilot challenges, Guide feedback, and staffing requirements.
- Post-pilot interviews: Pilot teams completed an interview at the end of pilot implementation to summarize and confirm all the information that had been provided during implementation and to collect final reflections.
- Final workshop: On November 17-18, 2021, the eight participating DOTs and their pilot teams convened for an interactive virtual workshop to share their experience piloting the Guide, to discuss what worked well and what needs improvement, and to brainstorm solutions.

3.3 Pilot Project Case Study Development

The pilot project feedback was used to assemble a short 2-4 page case study summary of each of the nine pilot projects. Each case study describes the project objectives, the relevant climate projections, and the potential impact on design. The case studies also highlight best practices and lessons learned by the pilot participants that could be useful to other DOTs. Each of the next nine chapters describes one of the case studies, starting with the Arizona DOT pilot project. A high level summary of the case studies is presented in Table 2

Table 2. Summary of pilot project case studies.

DOT	Project Summary	Project Type	Method to Project Precipitation/SLR	Projected Increase in Precipitation/SLR (Worst-cast Scenario)	Method to Project Design Discharge/SLR	Projected Increase in Design Discharge/SLR (Worst-case Scenario)	Methods to Calculate Design Impacts	Impacts of Potential Concern
AZ	Bridge renovation project considering temperature and precipitation	Inland hydrology	10-step procedure	+14%	N/A	N/A	Soil and Erosion Testing Services for Bridge Scour and Bayesian Belief Network.	Projected increase in drought could destabilize sediment. Projected increase in flooding and vegetation change that could increase scour risk.
CO	Evaluation or bridge scour at Colorado River bridge and Chacuaco Creek bridge	Inland hydrology	10-step procedure	+5.9%	Trends in historic discharge, HEC-HMS rainfall-runoff model, regression equations	+23%	Bridge scour design equations.	None. No trend in discharge detected at Colorado River. Highest projected discharge values were below the original design discharge..
FL	Evaluation of design for 2 bridges considering SLR	Coastal hydrology	USACE Sea Level Calculator, deterministic equations, probabilistic modeling	N/A	N/A	+1.12 m SLR	Monte Carlo simulation of SLR and ADCIRC/SWAN modeling	Wave loading on the design likely quadruples with SLR, which would threaten bridge stability.
IA	Evaluate level of service for two bridges under climate change	Inland hydrology	10-step procedure	+28%	HEC-1 rainfall runoff model; Index approach	N/A	Flood frequency analysis	500-yer level of service at first site could drop to 100-year level and from 50-year to 20-year at second site

Table is continued on next page.

Table 2 (cont.). Summary of pilot project case studies.

DOT	Project Summary	Project Type	Method to Project Precipitation/SLR	Projected Increase in Precipitation/SLR (Worst-cast Scenario)	Method to Project Design Discharge/SLR	Projected Increase in Design Discharge/SLR (Worst-case Scenario)	Methods to Calculate Design Impacts	Impacts of Potential Concern
MD	Evaluation of inland urban reconstruction project	Inland hydrology	10-step procedure	+15%	TR-20	+33%	Various models and design equations	Significant increase in headwater to twin culvert under RCP 8.5 scenario.
ME	Evaluate culvert design under projected precipitation	Inland hydrology	10-step procedure	+30%	Rational method	N/A	Design equations	Project culverts diameters must be increased ~ 3 to 6 inches to meet design standards at end-of-century.
NC	Interstate widening and resiliency project	Inland hydrology	10-step procedure	+24%	HEC-RAS rain-on-grid model	N/A	HEC-RAS rain-on-grid model	Up to 2 ft increase in flooding along road profile during end-of-century 100-year rainfall.
NC	Evaluate effects of SLR on coastal bridge	Coastal hydrology	MIKE 21 coastal hydrodynamic modeling	N/A	N/A	+4.4 ft SLR	Monte Carlo Simulation	Developed lookup tables with probability of extreme and nuisance flooding over asset lifetime.
OR	Evaluate scour and flood exposure to coastal bridge	Coastal and Inland hydrology	10-step procedure	+14%	USGS regression equations	Projected flows less than values used in design.	HEC-RAS modelling of scour and flood levels	No impacts due to conservative design discharge values.

N/A: not applicable or not available

Chapter 4

Arizona DOT Pilot Project

4.1 Introduction

The Arizona DOT (ADOT) pilot team used the Guide to support development of a natural hazard resilience assessment for the State Route (SR) 80 St. David Bridge replacement project in St. David, AZ (see Figure 2). The St. David Bridge is a scour critical, three-span continuous steel plate girder bridge on State Route 80, milepost 298.79. The facility crosses the San Pedro River at the confluence with Dragoon Wash. The contributing watershed is over 2,000 square miles with headwaters in Mexico.

The objective of pilot team was to understand how changes in climate could impact the safety, reliability, and overall life cycle of the bridge. In particular, the study looked at whether resiliency enhancements were needed to address (1) severe erosion at the site due to the convergence of two river systems at the project site, (2) concerns the bridge could overtop during a 50-year storm event, (3) field condition changes between the 1960s as-builts and 2022 in relation to conveying the 50, 100, and 500 year event, and (4) projected climate model outputs to the year 2100.

In addition to piloting methods in the Guide, this project developed and piloted other innovative approaches to resiliency assessment including probabilistic modeling of climate and extreme weather loading, LiDAR-based scour and overbank mapping; and worked with the J. Sterling Jones Hydraulics Laboratory at the FHWA's Turner-Fairbank Highway Research Center on computational flow dynamics (CFD) simulation of pressure flow conditions.

4.2 Climate Conditions

The ADOT pilot team used the Guide to conduct a level 4 analysis of the bridge's vulnerability to climate change including precipitation and temperature. The pilot team followed the Guide's recommendations to determine the climate conditions as follows:

- Obtained historic rainfall from the NOAA Atlas-14 dataset.
- Selected a baseline (1950-1999) and a future period (2050-2099) for analysis.
- Selected the RCP 4.5 and 8.5 climate emissions scenarios for evaluation.
- Selected and compared ensembles of two different types of CMIP5 high-resolution climate projections: 19 Bias Correction Constructed Analog (BCCA) GCMs and 28 Localized Constructed Analog (LOCA) GCMs. Downscaled datasets from the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections website.
- Used the FHWA CMIP Climate Data Processing Tool to analyze GCM data and extract key temperature and precipitation metrics under baseline and future conditions.

4.3 Projected Impacts on Bridge Resilience

The BCCA and LOCA GCM ensembles projected a much hotter and a modestly wetter future in the vicinity of the study site. Under the RCP 8.5 scenario, the average annual mean temperature is projected to increase 7.9 °F and the average number of days over 100 °F is projected to increase from less than 14 to more than 60 by 2050-2099. Under the same conditions, the median 24-hour 100-year precipitation event is projected to increase between 7% and 14% percent, although the confidence limits indicate relatively high uncertainty with projections ranging from a 40% precipitation decrease to a more than 50% increase.

The pilot team used the projections to conduct an initial regional risk analysis, which found relatively high increase in risk due to temperature changes and more uncertain risk from precipitation changes. The main risks due to increasing temperature are increase in pavement deformation and thermal expansion, an extension of construction work halts due to high temperature, and a rise of heat-related worker illness and fatigue. The main risks due to any increase in extreme precipitation are greater flooding, higher bridge scour, and more frequency mudslides and washouts.

4.4 Recommendations on Bridge Design

The ADOT pilot team provisionally recommended a number of resiliency enhancements to the design of the bridge replacement.

- Reduce the number of bridge spans in the design that are subject to erosion;
- Deepen the vertical supports including bridge and abutment piers;
- Make better use of the existing bridge abutments; and
- Raise the bridge profile.

These recommendations will be reviewed and potentially modified in the next phase of design. In addition, the pilot team recommended reviewing guidelines and specification for heat-resistant pavement mix, to ensure they are robust as temperatures of 110 °F and above become more common and potentially longer-lasting.

4.5 Other Findings

As part of a broader project, the ADOT pilot team developed a statistical Bayesian Network model to assess the probability of scour failure at the St. David's bridge under different climate projections. The model gives due consideration to protective measures, such as riprap around abutments, and can be used to optimize the resilient design of new structures. The model showed, for example, that the probability of St. David's bridge scour failure during the 50-year storm event is ten-times higher under potential climate change scenarios. At the same time, the model showed that this increased risk could be more than mitigated by a 15% increase in the depth of abutment and pier foundations depth.

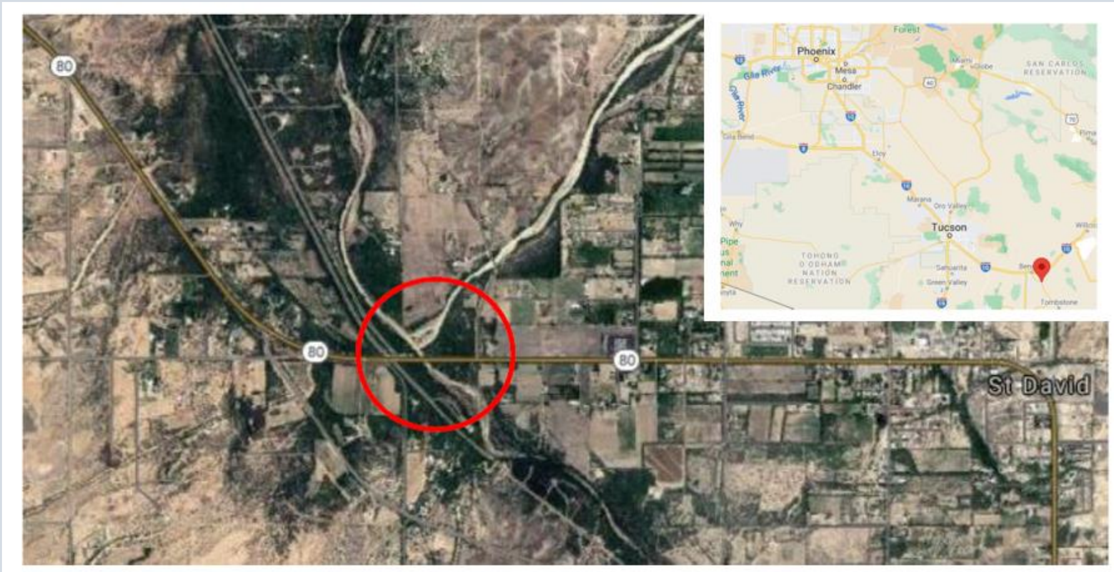


Figure 2. Location of ADOT pilot site.

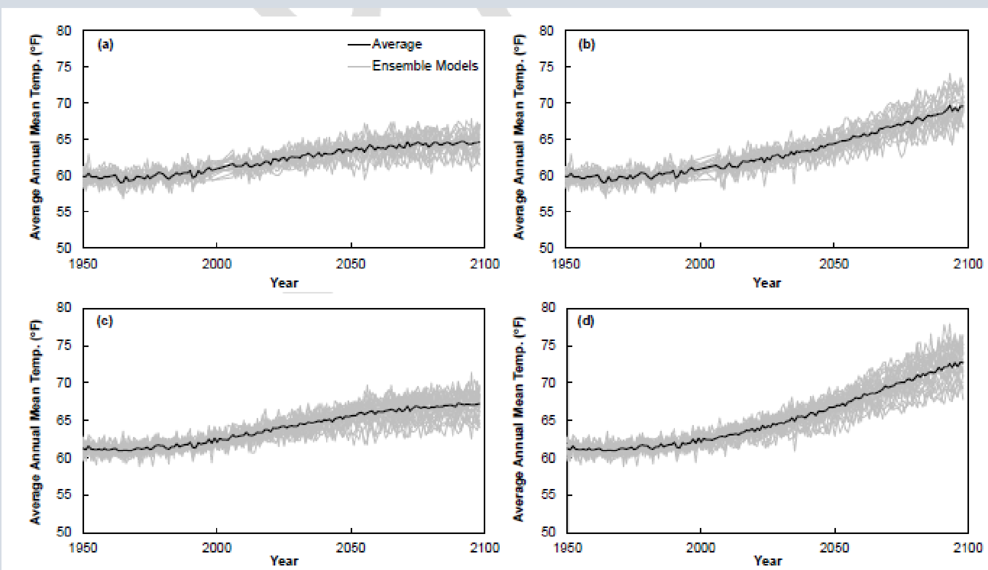


Figure 3 Predicted average annual mean temperature for 2021-2099 using (a) BCCAv2-RCP4.5, (b) BCCAv2-RCP8.5, (c) LOCA-RCP4.5, and (d) LOCA-RCP8.5 at the ADOT pilot site.

Chapter 5

Colorado DOT Pilot Project

5.1 Introduction

The Colorado DOT (CDOT) pilot team used the Guide to investigate the potential effect of climate change on scour at two bridge projects. Bridge F-50-R is a 445 ft bridge that spans the Colorado River on Highway 13 (referred to as the Colorado River bridge). There is an embankment failure upstream that threatens the abutment, and river shifts have caused adverse flow angles to attack the piers. Bridge P-22-D is a 110 ft bridge that spans the Chacuaco Creek on U.S. Highway 160 (referred to as the Chacauco Creek Bridge). The average daily traffic over the two bridges is 17,000 and 190, respectively. Both bridges are on the CDOT critical scour list due to potential for severe scour.

The pilot aimed to answer the following questions:

- What are the projected effects of climate change on the local hydrology?
- What are the projected effects on the system's hydraulics (discharge, velocity, shear stresses)?
- How do the projected hydrologic and hydraulics changes affect local bridge scour?
- What additional scour countermeasures (if any) are needed to mitigate the projected effects of climate change?

5.2 Historic Scour Analysis (Colorado River Bridge)

For the Colorado River bridge, the CDOT pilot team followed the methods in Chapter 5 of the Guide to project future discharge based on trends in historical discharges at nearby gauges. The bridge is close to both an upstream and downstream USGS river gauge with over 80 years of data. The pilot team used the Mann-Kendall test to evaluate the data record and found no statistically significant increasing trend in peak flows over the period of record (see Figure 4). Then the pilot team used Bulletin 17C to calculate the design flow with the modern gauge record, and found that even the upper confidence limit was lower than the original design discharge. The pilot team concluded that the Colorado River bridge was designed to a conservative design discharge that is very likely – based on historic trends – to remain resilient to peak discharges over the lifetime of the bridge.

5.3 Climate Conditions (Chacuaco Creek Bridge)

The Chacuaco Creek bridge was not near a USGS gauge. Instead, CDOT used the Guide to perform a level 3 analysis of the effects of climate change on the design discharge. CDOT followed recommendations in the Guide to determine the climate conditions for the analysis as follows.

- Obtained historic rainfall with confidence intervals from the NOAA Atlas-14 dataset.
- Selected a baseline and future time period (2006-2050) consistent with the expected lifetime of the bridge.
- Selected the RCP 4.5 and RCP 8.5 climate emission scenarios for evaluation.

- Selected all 32 RCP models available for analysis in the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections website.
- Used the CMIP Tool to calculate the precipitation change factors.

5.4 Projected Impacts on Hydrology

The CDOT pilot team used the Guide's 10-step procedure to estimate precipitation quantiles (see Guide Chapter 6) at the Chacuaco Creek bridge. The 100-year and 500-year 24-hour rainfall is projected to increase by +5.9% for both the RCP 4.5 and RCP 8.5 emission scenarios. CDOT used the rainfall projections to estimate the 100-year and 500-year discharge using two different methods from the Guide: the HEC-HMS rainfall runoff model (see Guide Chapter 6) and the USGS regression equations (see Guide Chapter 7). Note that the regression equations could be used because the 100-year 24-hour rainfall intensity is one of the regional USGS regression equation parameters.

The CDOT pilot team found that the projected discharge under existing and future conditions are very sensitive to the method used to do the calculation (see results in Table 3). For example, the 500-year discharge was projected to be significantly smaller when using the rainfall-runoff method (12,370 cfs) than when using the USGS regression equations (19,280 cfs). Furthermore, the 500-year discharge under climate change was projected to increase +9% using the rainfall-runoff method and +23% using the regression equations.

Table 3. Design discharge calculations for CDOT pilot at Chacuaco Creek bridge.

	Historic Baseline Discharge		Projected Discharge (2006-2050)	
Source	100-yr (cfs)	500-yr (cfs)	100-yr (cfs)	500-year (cfs)
HEC-HMS	8,550	12,370	9,340 (+9%)	13,450 (+9%)
USGS Regression Equations	9,720	19,280	11,680 (+20%)	23,740 (+23%)
Design Discharge	-	19,280	-	-

5.5 Projected Impacts on Infrastructure

The CDOT pilot team did preliminary analysis on the potential impact of the projected discharges on scour at the Chacuaco Creek bridge. Under future conditions, the stream velocities would increase +9% for the 100-year event and +20% for the 500-year event. Scour countermeasure would need to be redesigned since larger riprap materials are not available in the region. Other options could include grouted boulder or matric riprap.

After reviewing the results, the CDOT pilot team decided that the bridge's original design discharge based on regression equations (19,280 cfs) and existing countermeasures are sufficiently conservative to account for projected increases due to climate change. The original discharge is based on the regression equations for the Colorado Foothill Regions even though a portion of the watershed is in the Plains region, which makes the result relatively conservative. Furthermore, the HEC-HMS model estimated much lower design discharge values under both existing and future conditions, which again suggests that the baseline regression equation values are sufficiently conservative.

5.6 Next Steps

The pilot team is sharing their results with a broader audience at CDOT. The agency is considering ways to incorporate the Guide methods into future design practices.

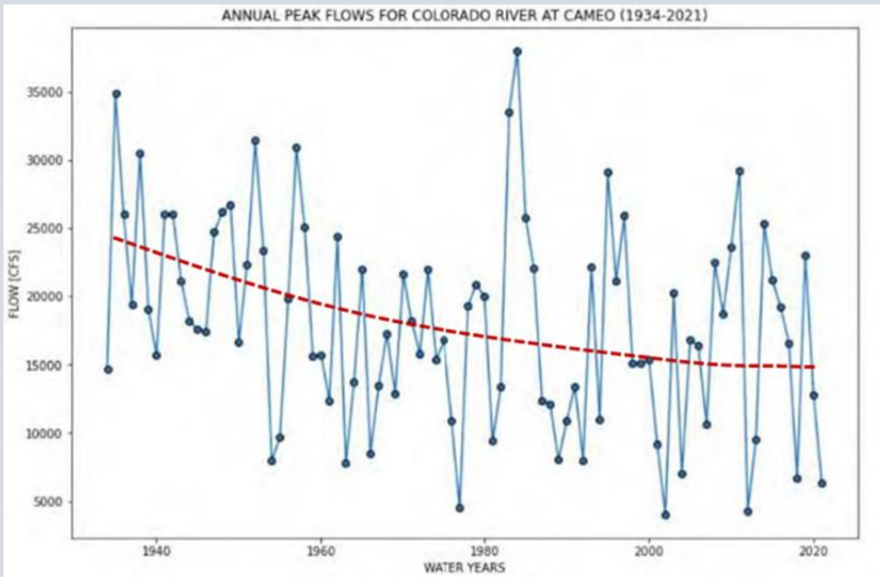


Figure 4. Plot of precipitation annual maximum series (in blue) and a smoothed average (red line) for the CDOT pilot at the Colorado River bridge.

Chapter 6

Florida DOT Pilot Project

6.1 Introduction

The Florida Department of Transportation (FDOT) used the Guide to a understand the potential impacts of climate change on a coastal replacement bridge project. The SR-30/US-98 bridge over St. Joe Inlet, Gulf County, FL, was being constructed at the time of the pilot to replace a 3-span tidally influenced bridge (see Figure 5).

FDOT arranged for two pilot teams to use the Guide to evaluate the bridge project at the same time, referred to here as pilot team A and pilot team B. This provided a unique opportunity to test the consistency of Guide implementation in the hands of different design teams. Both pilot teams produced reports which are included in the Appendices for reference. The main question the pilot teams were trying to answer was how will project SLR affect clearance and wave loading at the project site.

6.2 Climate Conditions

Pilot team A followed the approach in the Guide to calculate a relative sea level rise (RSLR) at the bridge using the USACE Sea Level Calculator. They estimated an RSLR of 0.859 m (2.81 ft) NAVD88 in 2071 based on the Apalachicola NOAA tide gauge and the 95th percentile SLR curve.

Pilot team B followed a similar procedure to calculate RSLR using the same Apalachicola tide gauge, but extended their analysis past 2071 to 2090 based on an assumption that the bridge would remain operational until then. The team calculated an RSLR of 1.12 m (3.67 ft) for the year 2090 based on a RCP 8.5 95th percentile projection.

6.3 Projected Impacts on Coastal Conditions

Pilot team A performed a level 2 analysis of coastal conditions at the project site. They modified existing numerical models to simulate the effect of SLR on storm surge height, scour velocities, and significant wave heights at the bridge. The projected SLR causes storm surge for the 50-year, 100-year, and 500-year event to increase by 3.3 ft, 2.6 ft, and 2.6 ft to a total height of 11.5 ft, 12.1 ft, and 15.4 ft respectively. Wave height is projected to increase by approximately +1 ft to a total of 4.9 ft. Flow velocities are expected to drop slightly at the bridge inlet.

Pilot team B performed both a level 1 analysis using the design equations in the Guide and a level 2 analysis using an existing ADCIRC hydrodynamic model. Table 4 summarizes the effect of SLR on coastal conditions using both approaches. The design equations and hydrodynamic model gave similar results. Pilot team B simulations also showed a drop in flow velocities near the bridge.

Table 4. Comparison of Guide coastal design equations and hydrodynamic modeling.

	Level 1 Design Equations*	Level 2 Hydrodynamic Modeling
WSE - 50-year (ft)	12.14	12.14
WSE – 100-year (ft)	13.55	13.41
WSE – 500-year (ft)	16.77	16.64
Wave height – 100-year (ft)	5.1	5.5
Wave period (sec)	6.3	6.3

* WSE equations assumed an amplification ratio of 1.1.

6.4 Projected Impacts on Wave Loading

Both Pilot team A and B simulated how the projected coastal conditions would affect wave forces on the bridge structure. Pilot team A found that the stillwater elevation at the bridge after SLR is very close to the bridge's low chord elevation, with wave forces increasing by 356% to 1550%. These projected wave forces are greater than the design wave forces that are specified in the bridge hydraulics report. Similarly, pilot team B concluded that SLR exposes the bridge low chord to the part of the wave with the highest kinetics and thus the largest wave loads. As a result, the wave loading increases on the order of four times the original calculations. The results from both pilot teams indicate that the bridge may be at substantial risk as future climate change evolves.

6.5 Other Findings

- With the help of the Guide, the two pilot teams produced very similar analyses and reached very similar conclusions. The results suggest that the Guide can yield consistent results when used by different engineering teams. One notable different between the pilots was the choice of time period: pilot team A projected their results out to 2071 while pilot team B projected their results to 2090.
- Pilot team B found that the projected effects of SLR are very sensitive to the ways that sea levels are assumed to evolve over time. The Guide design equations recommend using the projected sea level at the end of the period of interest (i.e., at the end of the structure's design life). The team developed an alternative probabilistic approach that accounts for the fact that sea levels and the risk they pose rise gradually over time.
- It was noted that the projected SLR could expose the bridge approach roads to regular tidal flooding by the end of the century. This flooding could make the bridge essentially unusable, regardless of the bridge deck height, and should be factored into any attempt to design for future conditions.

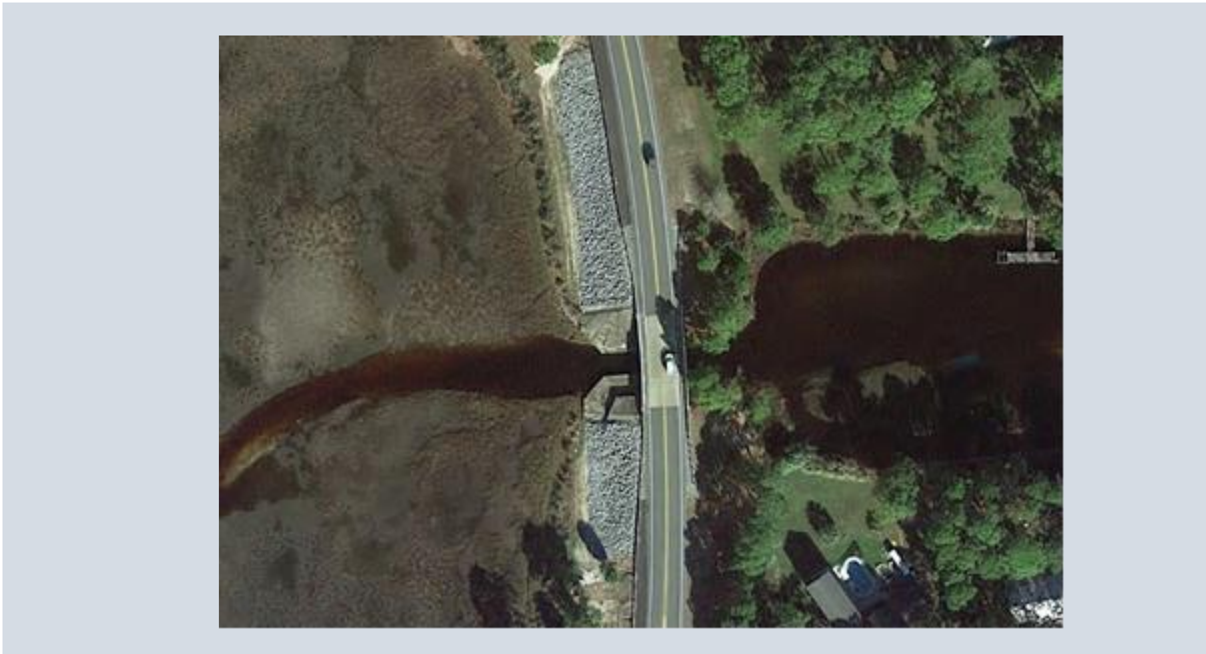


Figure 5. Image of study site for the Florida DOT project.

Chapter 7

Iowa DOT Pilot Project

7.1 Introduction

Iowa DOT used the Guide to evaluate the impact of projected increases in precipitation on two bridge projects on IA 3 near the City of Dumont (see Figure 6). The first bridge at Hartgrave Creek will be improved in planned roadway reconstruction. The roadway will form a Line of Protection (LOP) that is designed to protect nearby communities with a 500-year level of service (LOS). The second bridge at West Fork River was recently completed and sits next to a dike that was designed to protect nearby communities with a 50-year LOS. A major goal of the pilot project was to estimate the level of service for the two structures under projected climate change.

7.2 Climate Conditions

The Iowa DOT pilot team conducted a level 3 analysis that incorporated climate change projections. The pilot team followed the Guide's recommendations to determine the climate conditions as follows:

- Obtained historic rainfall from the NOAA Atlas-14 dataset.
- Selected a 1950-1999 baseline period, a 2025-2061 future period to represent the initial 30+ years of service, and a 2061-2099 future period to represent the following 30+ years of service:
- Selected the RCP 4.5 and 8.5 climate emissions scenarios for evaluation.
- Selected the 14 Group 1 models recommended in the Guide for evaluation. Downloaded GCM data from the DCHP website and processed them using the FHWA CMIP Tool.

7.3 Projected Impacts on Hydrology

The pilot team used the Guide's 10-step procedure to project 72-hour precipitation quantiles. For various return periods and the two emission scenarios, the analysis projected 72-hour rainfall to increase from +4% to +19% over the first 30-years of service and from +19% to +28% over the following 30-years of service (see Figure 7).

The pilot team used the projected precipitation with an index approach to estimate the projected design discharge. First, the historical flood frequency curve was obtained using USGS regression equations. Note that the local regression equation does not have a precipitation term and could not be used to directly project the future design discharge. Instead, a simple lumped-parameter hydrologic model (HEC-1) was built and forced with historical and projected rainfall data, and the results were used to calculate a ratio of future to baseline discharge for different return periods up to 10-years. The ratios were applied to the historical flood frequency curve to estimate the projected flood frequency curve (see Figure 8).

7.4 Projected Impacts on Infrastructure

Based on the projected hydrology, the pilot team estimated that the 500-year LOS at the Hartgrave Creek bridge could drop to a 100-year level of service over the next few decades. An adaptable design and/or further elevation of the roadway should be considered. Similarly, the 50-year LOS at the West Fork River bridge could drop to a 20-year LOS within a few decades. The dike could be raised as needed to maintain the desired LOS.

7.5 Other Findings

- The pilot team found it useful to consider the effect of climate change on antecedent storm moisture in their analysis. The peak runoff can be very sensitive to changes in the antecedent moisture, and the antecedent moisture can in turn be very sensitive to changes in the regional rainfall pattern.
- The pilot team made potentially useful modification to the index approach described in the Guide Chapter 8. The Guide recommends calculating a single projected/baseline ratio for the 10-year event (see Guide pg. 86 step 3) and applying it to all other return intervals. By contrast, the pilot team calculated and applied a separate projected/baseline ratio for return intervals up to the 10-year (i.e., the 2-year, 5-year, and 10-year). The pilot team thought that the variability in the projected/baseline ratios at different return periods were physically meaningful and worth incorporating into the calculation.
- To streamline the Guide's 10-step procedure and reduce the potential for miscalculations, the pilot team developed a set of gridded rasters with precipitation change factors for the entire state of Iowa. The team used the FHWA CMIP tool to calculate the change factors for different emission scenarios and then smoothed the cell-to-cell variability using a 1 degree averaging window.

Figure 6. Aerial image of Hartgrave Creek bridge (left) and west Fork Cedar River (right) for the Iowa DOT pilot.

Rainfall Data -

Baseline Hydrology NOAA Atlas 14 Volume 8 Rainfall Duration 72 Hr		Baseline CMIP Dataset 1950-2010 in. - 24 Hr.	Precipitation (Inches) 72 Hr. Duration							
			Projected RCP4.5 2025-2061		Projected RCP4.5 2062-2099		Projected RCP8.5 2025-2061		Projected RCP8.5 2061-2099	
Return Per	D (in)		Ratio P/B	Projected D (in)	Ratio P/B	Projected D (in)	Ratio P/B	Projected D (in)	Ratio P/B	Projected D (in)
2YR	3.57	1.54	1.08	3.86	1.11	3.96	1.05	3.75	1.15	4.11
5YR	4.59	2.09	1.12	5.14	1.17	5.37	1.04	4.77	1.20	5.51
10YR	5.44	2.45	1.14	6.20	1.19	6.47	1.04	5.66	1.22	6.64
25YR	6.66	2.90	1.14	7.59	1.19	7.93	1.04	6.93	1.22	8.13
50YR	7.67	3.24	1.14	8.74	1.19	9.13	1.04	7.98	1.22	9.36
100YR	8.75	3.58	1.14	9.98	1.19	10.41	1.04	9.10	1.22	10.68
200YR	9.89		1.14	11.27	1.19	11.77	1.04	10.29	1.22	12.07
500YR	11.50	4.35	1.14	13.11	1.19	13.69	1.04	11.96	1.22	14.03
1000YR	12.80		1.14	14.59	1.19	15.23	1.04	13.31	1.22	15.62
		Ratio Range 10%-0.2%:	(1.14-1.19)		(1.19-1.25)		(1.04-1.04)		(1.22-1.28)	

Figure 7. Projected 72-hr design precipitation event estimates from the Iowa DOT study.

Discharge Data -

Baseline Hydrology Model Results		Projected RCP4.5 2025-2061		Projected RCP4.5 2062-2099		Projected RCP8.5 2025-2061		Projected RCP8.5 2062-2099		NRCS ARC III CN (ARC II CN Used Baseline Hydrology)			Discharge Estimate Current Methology Assumed Ratio		Projected Future Discharge
Return Period	Q (cfs)	Q (cfs)	Ratio P/B	Q (cfs)	Ratio P/B	Q (cfs)	Ratio P/B	Q (cfs)	Ratio P/B	Q (cfs)	Ratio P/B	Wtg. P/B	Q (cfs)	Ratio P/C	Q (cfs)
										Fraction Of Ratio Used:		0.2			
2YR	2,311	2,812	1.22	2,993	1.30	2,618	1.13	3,271	1.42	5,826	2.52	1.30	2,100	1.48	3,108
5YR	4,240	5,410	1.28	5,923	1.40	4,613	1.09	6,242	1.47	8,783	2.07	1.21	4,100	1.45	5,945
10YR	6,130	7,935	1.29	8,604	1.40	6,640	1.08	9,031	1.47	11,415	1.86	1.17	5,500	1.42	7,810
25YR	9,188	11,633	1.27	12,558	1.37	9,884	1.08	13,108	1.43	15,379	1.67	1.13	7,700	1.39	10,703
50YR	11,938	14,920	1.25	16,037	1.34	12,788	1.07	16,703	1.40	18,755	1.57	1.11	9,300	1.37	12,741
100YR	15,066	18,659	1.24	19,945	1.32	16,075	1.07	20,759	1.38	22,465	1.49	1.10	11,100	1.35	14,985
200YR	18,528	22,717	1.23	24,264	1.31	19,729	1.06	25,198	1.36	26,457	1.43	1.09	13,400	1.33	17,822
500YR	23,643	28,729	1.22	30,590	1.29	25,083	1.06	31,686	1.34	32,212	1.36	1.07	15,200	1.31	19,912
1000YR	27,905	33,700	1.21	35,799	1.28	29,543	1.06	37,084	1.33	36,906	1.32	1.06			

Figure 8. Projected design discharge event estimate from the Iowa DOT study.

Chapter 8

Maryland DOT Pilot Project

8.1 Introduction

The Maryland DOT (MDOT) pilot team used the Guide to evaluate the effect of climate change on an active design project at Great Mills, MD in St. Mary's County on the Chesapeake Bay (see Figure 9). This urban reconstruction project will upgrade a quarter-mile stretch of MD Route 5 with road widening, drainage improvements, stormwater management, and stream stabilization. When the pilot began, the design phase for the project was past 65 percent complete. Due to the advanced stage of work, the pilot did not consider potential design changes. Rather, the pilot aimed to understand whether MDOT should anticipate an increase in roadway flooding or drainage complaints over time if the project was designed using current criteria and standards.

8.2 Climate Conditions

MDOT used the Guide to perform level 1, level 2, and level 3 analyses. Level 1 analysis calculates the design discharge based on historical data. Level 2 analyses includes level 1 analysis, and also calculates the design discharge based on historical confidence limits. Level 3 analysis includes level 1 and 2 analyses, while also calculating the design discharge based on projected information and confidence limits. MDOT followed recommendations in the Guide to determine the climate conditions as follows.

- Obtained historic rainfall with confidence intervals from the NOAA Atlas-14 dataset.
- Selected a baseline (1950-1999) and future (2060-2099) time period for analysis. The 2060-2099 period was selected to cover the second half of the estimated 75-year service life of the proposed concrete drainage pipes.
- Selected the RCP 4.5 and RCP 8.5 climate emissions scenarios for evaluation. RCP 4.5 was seen as a more optimistic scenario in which emission peak around 2040. RCP 8.5 was seen as a worst case scenario where emissions continue rising to the end of the century.
- Selected the 14 Group 1 models recommended in the Guide for evaluation. The FHWA CMIP Tool was used to calculate change factors.

8.3 Projected Impacts on Hydrology

MDOT completed the 10-step procedure to estimate projected precipitation quantiles at the project site. Figure 10 shows the projected intensity frequency curve for a 24-hour storm based on historic observations, the upper confidence limit (UCL) of historic observations, the RCP 4.5 future emissions scenario, and the RCP 8.5 future emissions scenario. The 10-year rainfall intensity changes +10% for the UCL rainfall, +3% for the RCP 4.5 scenario, and +15% for the RCP 8.5 scenario. The intensity frequency curve for the 5-minute rainfall event was assumed to increase the same percentage as the 24-hour rainfall. The 5 minute rainfall event was used in subsequent calculations, to match the roughly 5 minute time of concentration of the drainage network.

MDOT used a simplified TR-20 model to estimate the peak discharge to a twin 36-inch culvert at the project site (see Table 5). The results show that the percentage increase in discharge ranges from +4% to +33% depending on the emissions scenario and time period. The increase in discharge is both (1) greater than the percentage increase in rainfall and (2) greater at lower storm frequencies than higher frequencies.

Table 5. Percent increase in discharge to twin 36" culvert over Atlas-14 discharges

	% Change over Atlas 14 (Historic) Discharges		
Storm Frequency	**Atlas 14 UCL**	**RCP 4.5**	**RCP 8.5**
2-yr	+17%	+17%	+33%
10-yr	+16%	+5%	+23%
25-yr	+13%	+4%	+18%
50-yr	+13%	+4%	+18%
100-yr	+14%	+4%	+19%

8.4 Projected Impacts on Infrastructure

The precipitation values were fed into various stormwater drainage models and design equations to calculate the expected change from the historic baseline to the future time-period. The key findings are listed below.

- Spread and inlet efficiency: projected increases in rainfall cause minimal increase in spread or loss of efficiency.
- Pipe capacity: projected increases in stormwater pipe flow do not necessitate increasing pipe sizes.
- Hydraulic grade lines (HGL): projected HGL for the proposed drainage network shows minimal increase and does not move outside the system.
- Culvert capacity: projected increases in design discharge to a twin 36-inch culvert under the Atlas-14 UCL and RCP 8.5 scenarios would cause a significant 9-to-12-inch increase in headwater compared to baseline conditions.
- Stormwater management facilities: projected increase in precipitation to a submerged gravel wetland does not overtop the facility and maintains similar levels of peak flow reduction.

8.5 Other Findings

- MDOT calculated the climate change indicator (CCI) to help decide whether to pursue a level 2 or level 3 analysis. The CCI varied from 0.26 for the 100-yr event under the RCP 4.5 scenario, which suggest the adequacy of a level 2 analysis, to 1.59 for the 2-yr event under the RCP 8.5 scenario, which suggests the need for a level 3 analysis.
- MDOT compared their results from the 10-step procedure for precipitation quantile estimation with values developed by researchers associated with the Mid-Atlantic Regional Integrated Sciences and Assessment (MARISA) Program. The projected increase in rainfall was broadly similar with minor differences. For example, the projected increase for different frequencies of the 24-hour rainfall under the RCP 4.5 scenario ranged from +3% to +11% for the 10-step procedure and +4% to +10% for the MARISA dataset.

8.6 Next Steps

MDOT is currently updating their Highway Drainage Manual and plans to incorporate methods to consider climate change in design.

Figure 9. Location of MDOT pilot study.

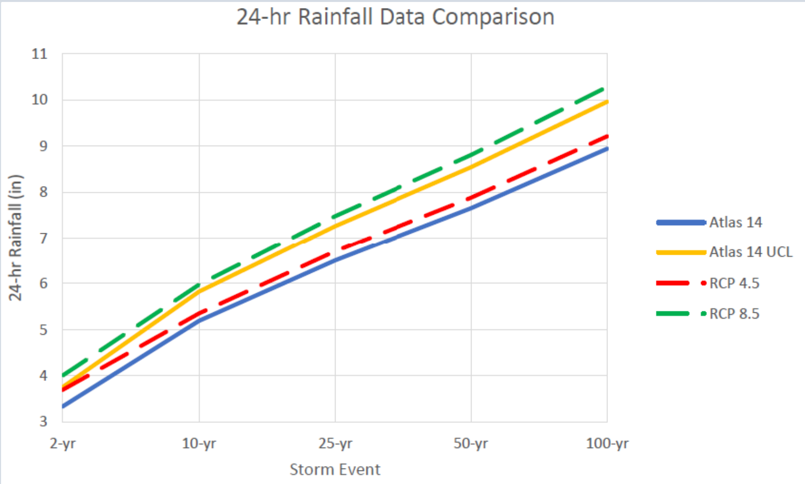


Figure 10. Projected IDF curve for MDOT project.

Chapter 9

Maine DOT Pilot Project

9.1 Introduction

The Maine Department of Transportation (DOT) used the Guide to help consider climate change in the design of culverts for the Brewer-Eddington connector project, which will join I-395 and Route 9 in central Maine (see map in Figure 11). The goal of the pilot was to understand (1) how much will the design precipitation event change under projected climate change and (2) to what extent are the current culvert designs adequate for the projected precipitation.

9.2 Climate Considerations

The Maine DOT pilot team used the Guide to conduct a level 3 analysis of the projected design precipitation at the project site. The pilot team followed the Guide's recommendations to determine the climate conditions as follows:

- Obtained historic rainfall from the NOAA Atlas-14 dataset.
- Selected a baseline (1950-1999) and three future periods: 2000-2033, 2033-2066, and 2066-2099.
- Selected the RCP 8.5 climate emission scenario for evaluation.
- Extracted projected/baseline precipitation ratios using the CMIP Tool.

9.3 Projected Impacts on Hydrology

The Maine DOT pilot team completed the 10-step procedure to estimate precipitation quantiles at the project site. For example, the 24-hour 10-year precipitation event is projected to increase approximately +10% by 2000-2033, +18% in 2033-2066, and +28% in 2066-2099 (see Figure 12). The precipitation projections were used to force a simple rainfall-runoff model (the Rational Method) to get design discharge projections for project culverts.

9.4 Projected Impacts on Infrastructure

The Brewer-Eddington connector project has more than one dozen stormwater cross-culverts and larger stream culverts. The Maine DOT design standard for culverts with a span less than 5 feet is that the headwater ratio should be less than 1.5 at the 50-year design flow. Larger culverts must have a headwater ratio less than 1 at the 100-year flow. The headwater ratio is the ratio of the depth of water at the culvert inlet to the height of the culvert opening. A headwater ratio of 1 is the "just full" condition where the water at the inlet is flush with the top of the culvert entrance.

The Maine DOT pilot team applied the design standard to determine how much the project culverts would have to be upsized to accommodate the projected design flow in 2099. Figure 13 shows a sampling of results for some smaller cross-culverts. Overall, the results suggest that the project culverts diameters must be increased by approximately 3 to 6 inches to continue to meet design standards in 2066-2099.

The pilot team generalized their results by calculating how much a culvert just meeting the design standard in the year 2000 would need to be upsized to meet standard in 2099. For example, a 12 inch culvert would have to be upsized by 1 inch, and a 30 inch culvert would have to be upsized by 3 inches culverts. The plots illustrate a "rule of thumb" that could be integrated into future design guidance.

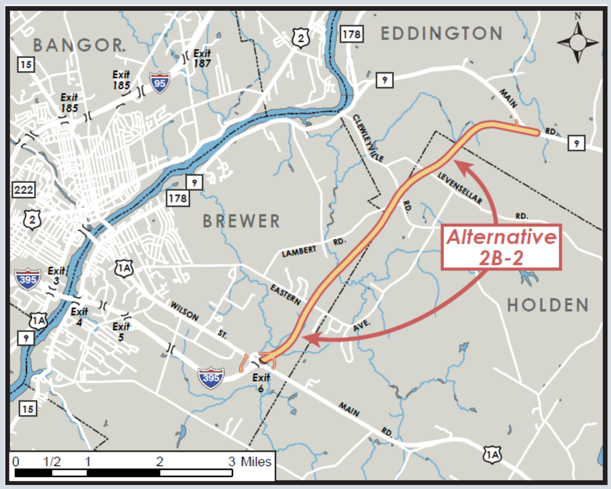


Figure 11. Map of project site for Maine DOT pilot.

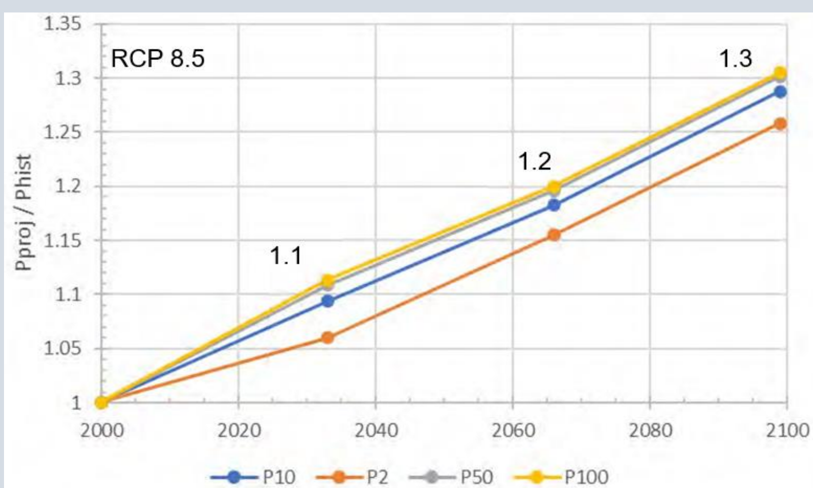


Figure 12. The ratio of projected 24-hour rainfall to historic rainfall depths for the Maine DOT pilot.

			T (yr)	2000	2033	2066	2099	*2000*
				50	50	50	50	*100*
Name	Sta	Aws (ac)	Design	$D_{1.5}$	$D_{1.5}$	$D_{1.5}$	$D_{1.5}$	D_1
DA11	117+35	22.83	*18*	18	18	19	20	*24*
DA10	131+25	21.85	*18*	18	18	19	20	*24*
DA9	133+75	37.85	*24*	20	21	22	23	*24*
DA8	159+50	32.79	*18*	19	20	21	22	*24*
DA7	180+75	20.05	*18*	17	18	19	19	*24*
DA6	999+91	12.39	*18*	15	16	17	17	*18*
DA5	227+00	18.38	*18*	17	18	18	19	*24*

Figure 13. Projected cross-culvert design requirements for different time periods for Maine DOT.

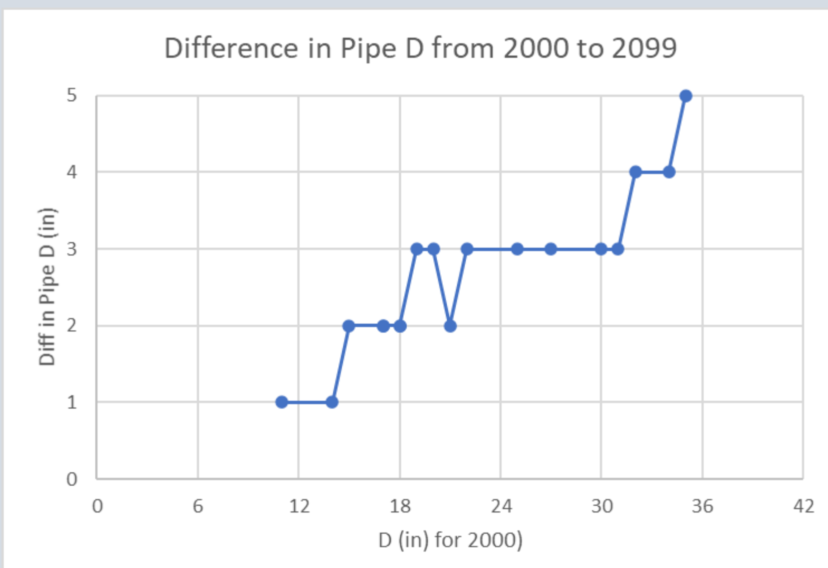


Figure 14. Theoretical amount of pipe upsizing needed to account for climate change in 2099 for a pipe that just meets the Maine DOT design standard in the year 2000.

Chapter 10

North Carolina DOT Pilot Project - Inland

10.1 Introduction

The North Carolina DOT (NCDOT) pilot team used the Guide to evaluate the potential effects of climate change on a planned I-95 highway widening and elevating project in the vicinity of Lumberton Regional Airport in Robeson County (see map in Figure 15). The project includes widening I-95 to 8 lanes and upgrading three interchanges with new bridges and ramps. The pilot project is described in detail in a final project report in the appendices.

The pilot aimed to answer the following questions about the project:

- How much is extreme rainfall at the project site projected to increase by 2100?
- How will projected increases in extreme rainfall affect flood elevations along the corridor, and how will the proposed system perform?

10.2 Climate Conditions

The NCDOT pilot team used the Guide to conduct a level 3 analysis of a riverine flood vulnerability at the project site. The pilot team followed the Guide's recommendations to determine the climate conditions as follows:

- Obtained historic rainfall from the NOAA Atlas-14 dataset.
- Selected a baseline (1950-1999) and four future periods (2000-2049, 2030-2060, 2050-2099, 2060-2099) for analysis. The results from the 2030-2060 and 2060-2099 periods are presented here, and the full results are in the final project report.
- Selected the RCP 4.5 and RCP 8.5 climate emissions scenarios for evaluation.
- Selected all 32 GCMs using LOCA downscaling that are available for download in the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections (DCHP) website.

10.3 Projected Impacts on Hydrology

The NCDOT pilot team completed the 10-step procedure to estimate precipitation quantiles at the project site. The pilot team split the contributing watershed into four sub-areas, downloaded GCM data for each sub-area from the DCHP website for 75 grid cells, and used the FHWA CMIP5 Tool to estimate the projected change in future precipitation for four sub-areas. The projected increase in the 100-year precipitation event in the four sub-areas for the RCP 8.5 scenario ranged from +7% to +11% for the 2030-2060 future period and from +11% to +24% for the 2060-2099 future period.

10.4 Projected Impacts on Infrastructure

The NCDOT pilot team developed a 2D rain-on-grid HEC-RAS model for the upstream watershed and project site. The model was calibrated using data from Hurricane Matthew and forced with baseline and projected future excess precipitation estimates. The pilot team also simulated a future Hurricane Matthew scenario, assuming the same percentage increases in rainfall as the 100-year event.

Model results show that the flood depth will increase more than 2 ft along stretches of I-95 due to projected increases in rainfall (see Figure 16). Fortunately, the project site is sufficiently elevated to avoid flooding during each rainfall scenario considered except the future Hurricane Matthew. As a result, no changes in the highway design were recommended. However, the modeling did show that two nearby stretches of highway are more exposed and will begin to experience flooding during the future 100-year rainfall event.

10.5 Other Findings

- The pilot team tested an approach to streamline the 10-step procedure by using only a subset of the watershed's 75 GCM grid cells. They found that using one grid cell from each of the watershed's four quadrants gave very similar results with less computational effort.
- The pilot team was initially surprised that the projected increase in the 100-year precipitation event was slightly higher for the RCP 4.5 scenario than the RCP 8.5 scenario for the 2030-2060 time period in one of the areas analyzed. This runs contrary to conventional wisdom, which says that extreme rainfall will be *lower* in the lower emissions scenario than the higher emissions scenario. The pilot team investigated the anomaly and found the rainfall during the RCP 4.5 scenario was indeed generally lower than the RCP 8.5 scenario, as expected, but that four high rain event outliers in the RCP 4.5 dataset made the 100-year precipitation unusually high. The project team later analyzed only the recommended 14 Group 1 LOCA models, and found the same result, which reflects the large natural variability in the GCM datasets.

Figure 15. Project site location for NCDOT.

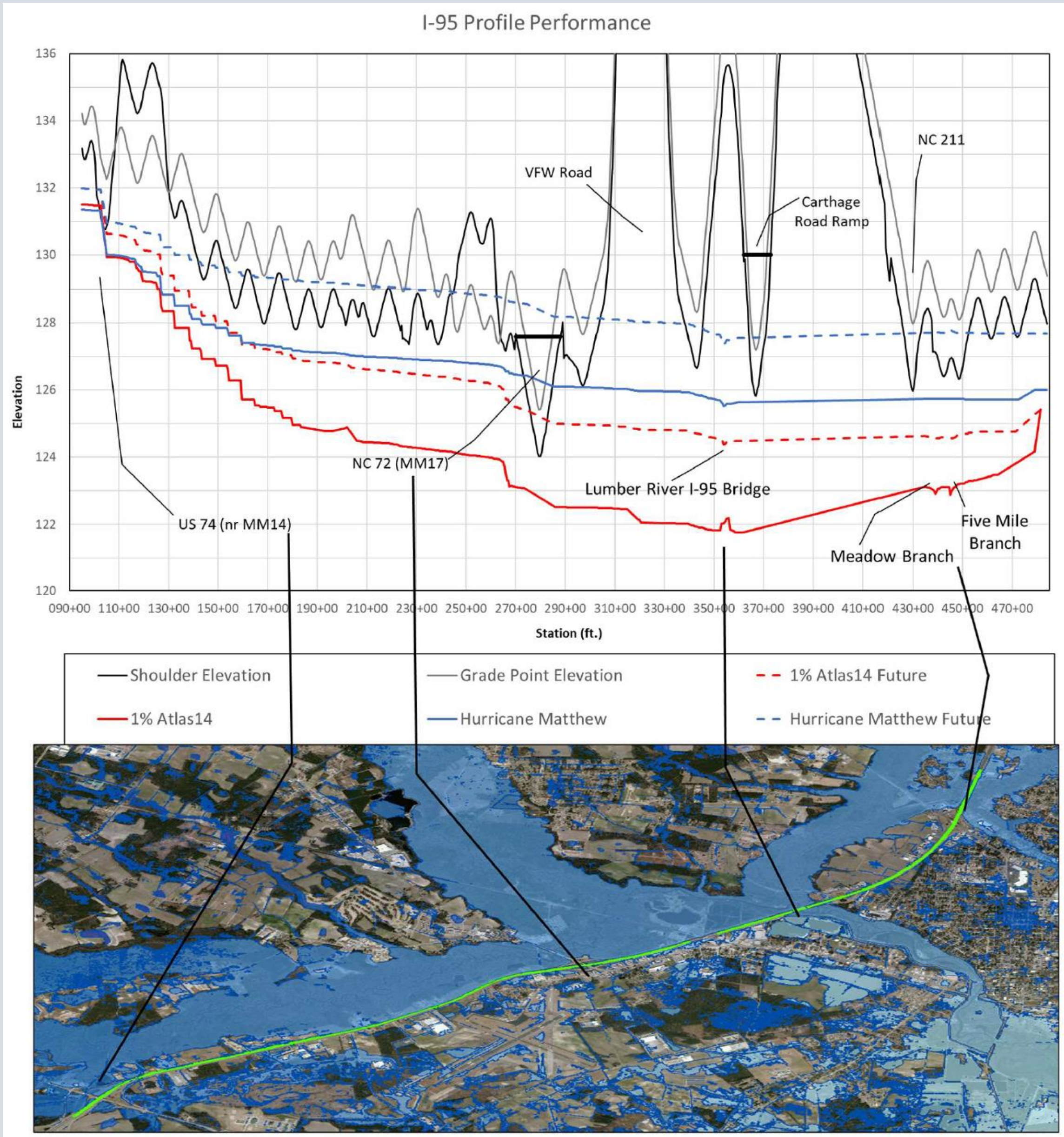


Figure 16. Profile of the flood profile along the I-95 study area under existing and future climate conditions from the NCDOT pilot study.

Chapter 11

North Carolina DOT Pilot Project - Coastal

11.1 Introduction

The North Carolina DOT (NCDOT) pilot team used the Guide to evaluate the potential effects of sea level rise (SLR) on flooding at a continuous concrete coastal bridge on North Carolina 24 (NC-24). The 2,277 ft bridge crosses the White Oak River to connect Swansboro to Cedar Point, Onslow County (Figure 17). The site is near an inlet to the Atlantic Ocean, approximately 3 miles to the south. As such, the bridge is vulnerable to coastal hazards, including flooding and storm surges. The pilot team aimed to answer several questions including:

- What is the likelihood of flooding over the bridge lifetime and how does it depend on SLR?
- What is the likelihood of nuisance flooding each year and how does it depend on SLR?

11.2 Climate Conditions

The NCDOT pilot team performed a hybrid level 1 and level 2 coastal analysis at the project site. The level 1 analysis used existing SLR estimates to evaluate coastal flood risk in a probabilistic framework with Monte Carlo simulation. The level 2 analysis used the MIKE 21 coastal hydrodynamic model to tease out the non-linear relationships between SLR, storm surge, and wave height. The pilot team reviewed the Guide's recommendations to help determine the climate conditions as follows:

- Selected a continuous time period of interest from 2020-2100. The nature of the probabilistic analysis did not require choosing more discrete future time periods.
- Selected the RCP 4.5 and RCP 8.5 climate emissions scenarios for evaluation.
- Selected the SLR estimates by Kopp et al. (2014) and Kopp et al. (2017), which assigns a probability to any particular level of relative sea rise at any time between now and 2100.

11.3 Nonlinear Surge – SLR Relationship

The pilot team ran a series of coastal storm models and evaluated the results to determine the non-linear relationship between SLR and storm surge. In general, a given rise in sea level causes a somewhat larger or smaller rise in total storm surge due to the nonlinear effect of water depth on storm surge propagation. The Guide suggests capturing this effect with a fixed amplification ratio. The pilot team introduced a more sophisticated method that allows the amplification ratio (which they redefine as a nonlinearity factor) to change as SLR increases. They found that the amplification ratio ranged from approximately 1.4 with low SLR to 1.2 with high SLR. The pilot team used these findings to improve the flood simulations described below.

11.4 Projected Impact on Coastal Flooding Over Project Life

The pilot team ran a probabilistic Monte Carlo simulation to determine the likelihood that the project site would flood to any given depth over the life of the project. First, the team reviewed FEMA coastal flood modeling results to extract the probability of different storm surge heights at the project site under baseline conditions. Then the project team ran 1 million Monte Carlo simulations that randomly sampled sea rise (up to 4.4 ft) and storm surge heights over discrete time periods until the end-of-century and used the outputs to calculate the probability of any total flood depth over time. A sample of the results are shown in Figure 18. It shows, for example, that the probability of flooding to 7 ft NAVD88 over a 40-year project lifetime is 79.6% assuming no SLR and 90.3% assuming the RCP 4.5 emissions scenario.

11.5 Projected Impact on Coastal Nuisance Flooding

The pilot team performed a similar analysis to estimate the probability of 1 or more nuisance flooding events in a year at different exceedance elevations. For example, the sample output in Figure 19 shows that that there is a 50% chance that there will be at least 1 flood event per year reaching 6 ft NAVD88 by 2093 assuming the K14 RCP 8.5 SLR projection.

11.6 Other Findings

- The study predicts a 5-10% increase in local wave heights between 2 feet and 5 feet of SLR.

11.7 Next Steps

This probabilistic water level analysis is providing a better basis for decision-making in design. For example, the projected increase in wave size could be addressed with larger sized stone for protecting slopes. NCDOT will be incorporating probabilistic SLR and storm flooding into coastal design projects. The results of this study can be combined with road elevation data to identify vulnerable areas and identify potential mitigation strategies. NCDOT will be updating coastal guidelines for climate adaptation concepts and resiliency.

Figure 17. NC-24 Bridge at Swansboro, NC.

No SLR

Level	Likelihood of Seeing At Least One Flood During Project Life			
Feet NAVD88	20 Years	40 Years	60 Years	80 Years
6	72.3%	92.3%	97.9%	99.4%
7	54.9%	79.6%	90.8%	95.9%
8	42.9%	67.4%	81.4%	89.4%
9	32.4%	54.2%	69.0%	79.0%
10	23.6%	41.6%	55.4%	66.0%
11	16.4%	30.2%	41.7%	51.4%
12	10.2%	19.4%	27.7%	35.1%
13	6.3%	12.1%	17.6%	22.8%
14	3.8%	7.4%	10.9%	14.3%
15	2.0%	3.9%	5.8%	7.7%

RCP 4.5

Level	Likelihood of Seeing At Least One Flood During Project Life			
Feet NAVD88	20 Years	40 Years	60 Years	80 Years
6	80.10%	97.90%	99.80%	100.00%
7	63.10%	90.30%	98.20%	99.70%
8	48.30%	77.90%	92.50%	97.90%
9	36.90%	64.80%	83.00%	92.90%
10	27.20%	51.60%	70.90%	84.30%
11	19.60%	39.20%	57.40%	72.60%
12	12.60%	27.50%	43.20%	58.30%
13	7.80%	17.70%	29.80%	43.10%
14	4.70%	11.10%	19.40%	29.70%
15	2.60%	6.50%	11.90%	19.10%

Figure 18. Probability of flooding during project life from NCDOT coastal pilot project.

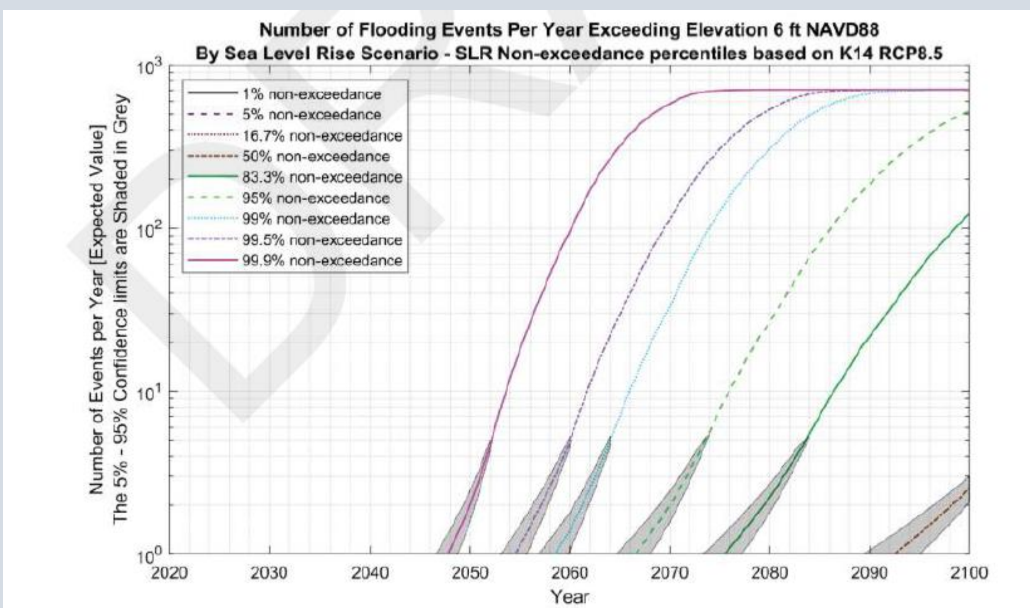


Figure 19. Nuisance flooding probability plot for the NCDOT pilot.

Chapter 12

Oregon DOT Pilot Project

12.1 Introduction

The Oregon Department of Transportation (ODOT) pilot team used the Guide to understand the potential impact of climate change on the Millport Slough Bridge on the Oregon Coast Highway (US 101). The 382 ft, 4 span bridge was recently reconstructed in 2011. The structure is adjacent to the coast and straddles a narrow channel, approximately 6 miles south of Kernville, OR (Figure 20). The pilot aimed to answer several questions including the following:

- How will climate change affect bridge scour and flood exposure?
- How sensitive are the results to the methods (e.g., GCM selection)?
- How consistent are the results to other data sources (e.g., USGS, historical record)?
- How could the design be changed to mitigate potential future issues?

12.2 Climate Considerations

The ODOT pilot team conducted a level 3 analysis of the inland hydrology and a level 1 analysis of the coastal dynamics. The level 3 analysis looked at the effect of projected change in rainfall on the structure, while the level 1 analysis focused on the effect of projected sea level rise (SLR). To begin, the pilot team followed the Guide's recommendations to determine the climate conditions as follows:

- Obtained historic rainfall from the NOAA Atlas-2 dataset.
- Selected a mid-century period (2040-2079) and a late century period (2060-2099).
- Selected the RCP 4.5 and 8.5 climate emissions scenarios for evaluation.
- Selected all 32 GCMs using LOCA downscaling that are available for download in the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections website. Also tested the 14 Group 1 GCMs recommended in the Guide.
- Calculated sea level rise based on historical trends in nearby NOAA tide gage and GMSLR for RCP 4.5 and RCP 8.5.

12.3 Projected Impacts on Hydrology

The pilot team used the 10-step procedure in the Guide to project the change in the design rainfall event due to climate change. They found that the projected increase in the design rainfall event ranges from +8% in mid-century for the RCP 4.5 scenario to +14% in late century for the RCP 8.5 scenario.

The pilot team used the regional USGS regression equation to estimate the design discharge in the future periods. The regression equation has a precipitation term, which was assigned the projected rainfall values. The projected discharge for all future scenarios was found to be lower than the historical values calculated for the FEMA Flood Insurance Study (FIS), which had been used to design the bridge.

12.4 Projected Impacts on Infrastructure

The pilot team built a HEC-RAS model at the bridge site using the projected inflows and tidal boundary conditions to assess the future exposure to flooding and scour. The team concluded that the existing design is resilient to projected changes and does not require design changes. This is because (1) it was designed to a very conservative design discharge that is greater than the projected future discharge and (2) it was reconstructed in 2011 with a seismic design that includes scour-resistant channel armoring and deep piles. The project team plans to repeat its analysis using the original bridge design, which was not a seismic design and is more similar to other bridges in the area.

12.5 Other Findings

- The pilot team noted that the average rainfall values in the GCM ensemble were significantly less than other sources including the historical record and the NOAA Atlas-2 estimates. This is the reason the team following the Guide’s recommendation and only used the GCM data to calculate the projected/baseline ratio, which was then applied to historical values.
- The team followed the 10-step procedure for 24-hour precipitation quantile estimation using all 32 GCMs from the DCHP website, and repeated the procedure using only the 14 Group 1 GCMs recommended in the Guide. They reported that the two set of GCMs gave very similar results.

Figure 20. Millport Slough Bridge for the ODOT pilot project.

Chapter 13

Lessons Learned

13.1 Staff Resources

DOTs have a broad mission and limited operating resources. It is important to understand the level of staffing effort required to implement the Guide for budgetary and planning purposes. To better understand the costs associated with the Guide, the nine pilot projects each answered survey questions about the amount of time and effort that was spent implementing their pilot projects.

Based on survey results, the DOTs and their implementing partners spent an average of 136 total staff hours on each pilot project. There was large variation in the amount of effort across pilots, which reflects the fact that the projects varied significantly in size and scope. Some pilots reported needing less than 50 staff hours while other pilots reporting needing more than 250 hours. In general, the coastal pilot projects were more complex with a higher average number of total staff hours (231 hours) than inland hydrology pilot projects (89 hours). The pilot teams engaged a variety of staff including entry level engineers (accounting for 20% of all reported hours), mid-level engineers (36%), senior engineers (26%), project managers (9%), and other positions such as GIS specialist (9%). None of the projects received support from a climate scientist.

The pilot participants also reported the amount of time that was spent on each of the key sections and chapters of the Guide (see

Table 6.). The pilots applied all the components of the Guide except for the chapter using continuous rainfall/runoff model simulations (Chapter 9), which would generally only be applied to Level 4 projects. Almost all of the pilots (8 out of 9) applied the methods in Chapter 3 to select an appropriate climate change scenario, while only a single pilot (1 out of 9) applied methods to project discharge based on index approaches (Chapter 8) or project coastal hazards using equations with design equations (Chapter 12). In general, the most time intensive steps were coastal applications, which generally involved detailed probabilistic evaluations.

Note that many of the pilot participants thought that the number of staff hours needed to implement the Guide procedures would decrease over time by as much as 25-50% due to experience effects.

13.2 Consistency of Implementation

It is important for the Guide to yield consistent results when applied to different projects by different engineering teams. For example, the projected change in future precipitation should be similar at neighboring project sites. The Guide recommends multiple tactics to help engineers produce consistent results, such as the averaging of GCM results over multiple grid cells to smooth random variation, the incorporation of simple flow charts and clear rules of thumb to reinforce engineering judgement, and encouragement to use spreadsheets and online calculators to minimize the potential for human error.

Table 6. Table summarizing the number of hours spent on chapters and sections of the Guide

Guide Section or Chapter	Procedure Name	Number of Pilot Projects that Applied the Procedure (Out of 9)	Average Amount of Time Spent per Pilot that Applied the Procedure (Hours)
2.3	Selecting a decision-making framework	6	5-10
3.1	Selecting climate scenarios	8	5-10
3.2	Selecting high-resolution climate projections	6	1-5
3.3	Selecting climate models	8	1-5
4.4	Calculating the climate change indicator	5	5-10
4.1 or 10.1	Selecting the appropriate level of analysis	5	5-10
5	Projecting discharge based on historic gage records	3	5-10
6	Projecting discharge using future rainfall in rainfall/runoff model	4	10-20
6	Projecting future rainfall	6	5-10
7	Projecting discharge using regression equations	3	5-10
8	Projecting discharge based on index approaches	1	5-10
9	Projecting discharge using continuous simulations	0	NA
11	Selecting sea level rise for design	2	50-100
12	Projecting coastal hazards using equations 12.1 to 12.4	1	25-50
NA	Determining the effect of projected future conditions on project design and performance	7	25-50
NA	Other task in the guidance (specify in comments)	2	5-10

Several pilot projects ran experiments that confirm the Guide gives reasonably consistent results under certain test conditions. As described in the case studies, the Maryland DOT followed the 10-step procedure to estimate projected precipitation and compared the results to an online repository of projected precipitation IDF curve data for the Chesapeake Bay Watershed developed by researchers associated with the MARISA program. The two sources of projected precipitation estimates gave almost identical results. The Florida DOT asked two different project teams to use the Guide to estimate the impact of potential effect of sea-level rise and storm surge on a coastal bridge. Once again, the two teams reached nearly identical conclusions about the projected future risk.

At the same time, the pilot projects identified issues with the Guide that could undermine the consistency of results. First, pilot participants said that the information needed to conduct a specific level of analysis (e.g., level 1 or 2) is spread throughout the entire Guide, which makes it easier to miss important steps and harder to develop a consistent workplan. The pilot participants recommended adding a section that summarizes the steps needed to complete different levels of analysis from start to finish. Second, at least one pilot project (CDOT) used different methods to estimate the projected design discharge and found that they yielded substantially different results.

13.3 Design Implications

DOTs may be apprehensive to use the Guide to evaluate infrastructure because of the perception that considering climate change will invariably require major design changes. In fact, the pilots reported a wide variety of design implications depending on the original objective of their pilot and the site conditions. In some pilot projects, design changes were not under consideration because the analysis was scoped to build institutional capacity or to understand future risks for planning purposes. In other cases, design changes were not recommended because either the climate projections did not show significant change or because the current project design was sufficiently resilient to withstand any projected change. Finally, a minority of the pilot projects did result in recommendations to address identified risks. Table 7 lists the potential design implications of Guide implementation and possible explanations based on the pilot experience.

Table 7. Potential design implications of Guide implementation.

Design Implication	Possible Explanation
Design changes not considered	Analysis scoped as an exercise to build institutional capacity Analysis scoped to understand future risks for planning purposes (e.g., non-design focused mitigation, adaptive risk management)
Design changes not recommended	Climate projections do not show significant change over period of interest Climate projections show significant change but project design is sufficiently resilient
Design changes recommended	Climate projections show significant change and project design is not sufficiently resilient

13.4 Additional Resource Summary

The pilot projects used a variety of modeling tools, references, and web tools that were recommended by the Guide. Pilot projects noted that the references to these resources were scattered throughout the Guide and potentially easy to overlook. In addition, pilot projects took advantage of many tools and references that were not mentioned in the Guide, in many cases because they were released after the Guide was written.

To make it easier for DOTs to identify and access these resources in the future, Table 8 has a list of helpful outside resources that were listed in the Guide. Table 9 has a list of resources that were not listed in the Guide but were used by the pilot DOTs and may be helpful to others.

Table 8. Tools mentioned in the Guide

Tool name	Description	Page
ADCIRC	Provides timely, high-resolution information on coastal storm surges, waves, flooding, and winds.	106
CERA	A web app for visualizing impending storm surge for active tropical cyclones in the United States.	101
EPA CREAT	Climate-related risk assessment tool for the water sector.	91, 97
HSPF	Simulates watershed hydrology and water quality for pollutants.	93,94,97
ICLUS database	Landcover change data, based on projections of population, housing density, and impervious surface for the United States.	83,93
NFHL	FEMA Digital Flood Insurance Maps in geospatial format for the entire United States.	101, 105
NWS-24	Reference for calculating geographically fixed depth-area ratios from dense networks of precipitation gauges.	73
NOAA ATLAS 14	Point-based precipitation frequency estimates for intensity and rainfall depth for 20 to 1,000-year events, exportable to CSV or shapefile.	29,31,32,46,51,56,58,59-61,72
NOAA IOOS COMT	A portal connecting federal agencies and research communities, and allows sharing of numerical models, observations and software tools.	102
STAR-ESDM	Climate data is based on a new bias correction and downscaling method that employs a signal processing approach to decompose observed and model-simulated temperature and precipitation into long-term trends.	
STWAVE	A steady-state, finite difference, spectral model based on the wave action balance equation.	106
SWAN	Model computes random, short-crested wind-generated waves in coastal regions and inland waters.	106
SWAT	A small watershed to river basin-scale model used to simulate the quality and quantity of surface and groundwater	93,94,97
SWMM	Storm water modeling tool for planning, analysis, and design related to stormwater runoff, combined and sanitary sewers, and other drainage systems.	90
USACE HEC-HMS	Simulate the complete hydrologic processes of dendritic watershed systems.	29,65
USACE ERDC CHS Web-Tool V2.0	A national coastal storm hazard data resource for probabilistic coastal hazard assessment (PCHA) results and statistics, including storm surge, waves, currents, wind, and astronomical tides.	101,102,132
USACE SLR Curve Calculator	Reports predicted sea-level change for three climate scenarios from 1992 forward.	111
Win TR-21	A single event watershed-scale runoff and routing model.	65

Table 9. Additional resources outside the Guidance

Tool Name	Description
ASCE-7	A standard for determining design wind loads.
Bureau of Reclamation Climate Data Archive	Downscaled CMIP5 climate and hydrological projections in netCDF format, suitable for input to the FHWA CMIP Data Processing Tool.
FHWA CMIP Data Processing Tool	Processes CMIP into a variety of climate variables useful for transportation planners.
HAZUS	FEMA risk assessment tool for earthquake, hurricane, and floods, capable of generating depth grids and storm surge maps with a Digital Elevation Model (DEM).
Mid-Atlantic Projected IDF Curves	Projected Intensity-Duration-Frequency (IDF) Curve Data Tool for the Chesapeake Bay Watershed and Virginia. Developed by researchers associated with the MARISA program.
MIKE 21	Commercial simulation engine for modeling tidal flows, storm surge, advection-dispersion, oil spills, water quality, wave propagation, and more.
SLOSH	A computerized numerical model for estimating storm surge heights, based on historical, hypothetical, or predicted hurricanes
TPF5 Soil and Erosion Testing Services for Bridge Scour Evaluation	A program for providing State DOTs with support for soil and erosion testing services for bridge projects over water crossings.
HEC-GeoHMS	Geospatial hydrology toolkit for engineers and hydrologists with limited GIS experience.
USACE HEC-RAS	Software tool for conducting one-dimensional steady flow, one and two-dimensional unsteady flow calculations, sediment transport/mobile bed computations, and water temperature/water quality modeling.
USGS StreamStats	A map-based user interface for delineating drainage areas, deriving basin characteristics, estimates of peak flow statistics, and more.

Chapter 14

Acronyms

AASHTO	American Association of State Highway Transportation Officials
ADCIRC	ADvanced CIRCulation storm surge model
ASCE-7	American Society of Civil Engineers Standard 7
BCA	Benefit-Cost Analysis
BCR	Benefit-Cost Ratio
CERA	Coastal Emergency Risks Assessment
CHS	Coastal Hazards System
COMT	Coastal and Ocean Model Testbed
ERDC	Engineer Research and Development Center
HSPF	Hydrologic Simulation Program
ICLUS	Integrated Climate and Land-Use Scenarios database
MARISA	Mid-Atlantic Regional Integrated Sciences and Assessments
NCHRP	National Cooperative Highway Research Program
NWS-24	National Weather Service Technical Report 24
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SLR	Sea Level Risk
STARESDM	Seasonal Trends and Analysis of Residuals dataset
SWAT	Soil and Water Assessment Tool
SWMM	Stormwater Management Model
TRB	Transportation Research Board
USACE	United States Army Corps of Engineers

List of Appendices (not included as part of this NCHRP Publication)

A. Arizona DOT

B. Florida DOT Team A

C. Florida DOT Team B

D. North Carolina DOT Inland

E. North Carolina DOT Coastal

F. Maryland DOT