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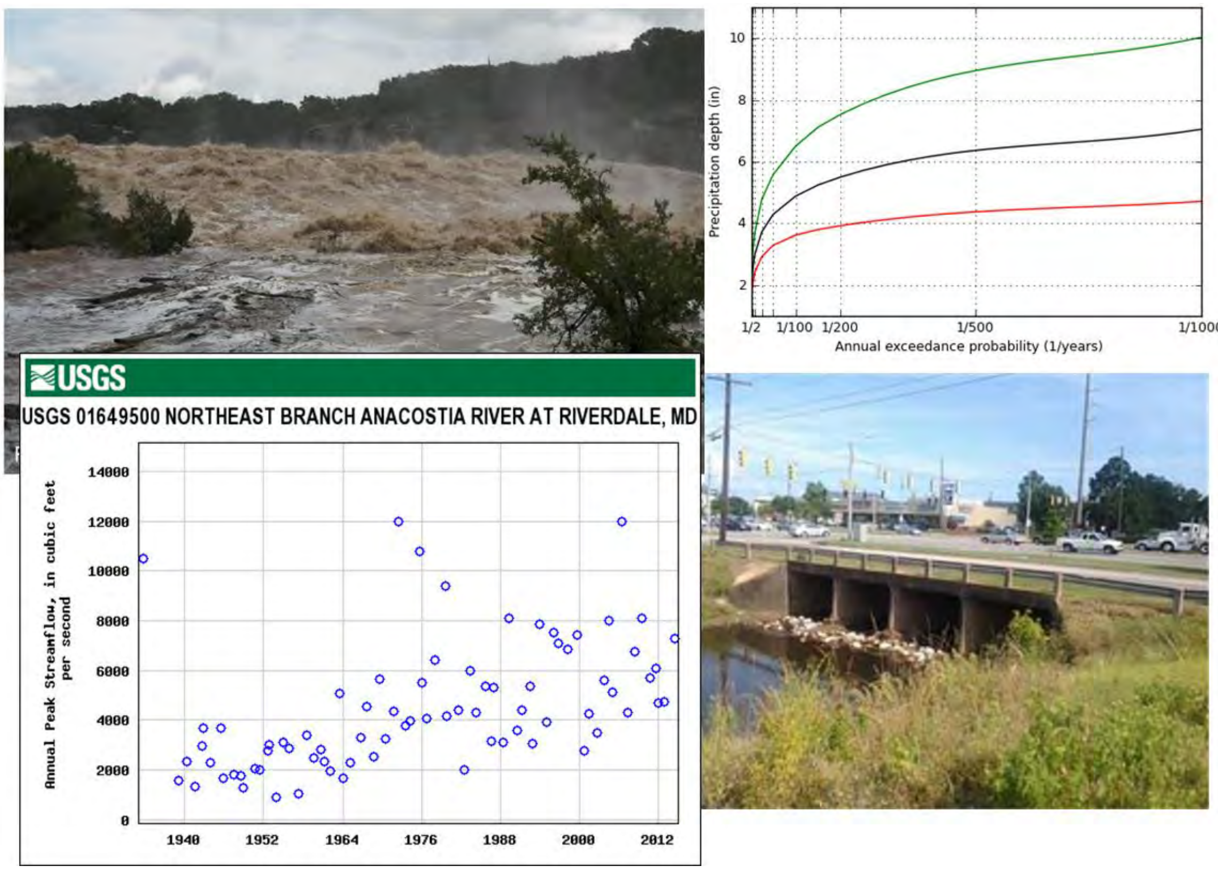

Highways in the River Environment- Floodplains, Extreme Events, Risk, and Resilience

U.S. Department of Transportation
Federal Highway Administration

Memorandum

Subject: **INFORMATION**: HEC-17 – Highways in the River Environment: Extreme Events, Risk and Resilience

Date: August 1, 2016

From: Joseph (Joe) Krolak, P.E.
Principal Hydraulic Engineer

In Reply Refer To: HIBS-20

To: FHWA Division Bridge Engineers & Staff
State DOT Hydraulic & Drainage Engineers

The FHWA Office of Bridges and Structures (HIBS), working with the Office of the Natural Environment (HEPN) and the Resource Center, are releasing Hydraulic Engineering Circular (HEC) 17, "Highways in the River Environment: Extreme Events, Risk and Resilience"[1]. In doing so, FHWA acknowledges the efforts of the team at Kilgore Consulting and Management, authors of the manual.

This HEC-17 manual is a major and significant update that provides technical guidance and methods for assessing the nexus of riverine and transportation as it relates to floods, floodplain policies, extreme events, climate change, risks, and resilience. An important focus is quantifying exposure to extreme flood events considering climate change and other sources of nonstationarity.

This focus aligns with FHWA policies and procedures relating to consideration of change, and effects of change upon a project's hydrology and hydraulics. For example, almost exactly 60 years ago, at the very beginning of the Interstate Highway System, the August 10, 1956 Policy and Procedure Memorandum 20-4 required:

> *"Designs for all [Interstate] culverts and bridges over streams shall … accommodate floods at least as great as that for a 50-year frequency or the greatest flood of record, whichever is the greater,* ***with the runoff based on the land development expected in the watershed 20 years hence*** *...."*

Today, the consideration of such change, particularly change associated with climate and extreme events, necessitates FHWA's goal that HEC-17 provides the transportation community with our understanding of the best current, actionable, science informed approaches to address such change in the river environment. In doing so, FHWA believes that this manual provides a complement to our October 2014 HEC-25, "Highways in the Coastal Environment: Assessing Extreme Events – Volume 2."

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[1]In April 1981, FHWA produced the 1st edition of HEC-17: "Design of Encroachments on Flood Plains Using Risk Analysis." This 2nd edition expands upon and supplements that April 1981 1st edition. However, FHWA believes the risk analyses in the 1st edition still provide useful approaches and practices for the transportation community.

Specifically, HEC-17 describes and discusses:

- FHWA and other floodplain policies and guidance
- Uncertainty associated with hydrologic models
- Nonstationarity and two drivers: climate change and land use/land cover changes
- Several tools for identifying and adjusting for trends in the historical record
- Techniques for projecting floods
- Global/regional climate models, downscaling techniques, and emissions scenarios
- Risk and resilience and the probabilistic nature of flood events

Recognizing that all plans and projects do not merit the same attention, HEC-17 also provides a five level analysis framework and specific guidance for addressing non-stationarity, including climate change. Finally, the manual provides case studies to illustrate several of the concepts.

In releasing this technical manual, FHWA understands that all of these topics only reflect an initial placeholder of a rapidly evolving scientific and engineering consensus effort.

For example, AASHTO, NCHRP, and other organizations are undertaking relevant and important research and studies that will increase our understanding of the science and advance the state of the practice. In recognition, FHWA plans to collect and update such information and provide further HEC-17 (and HEC-25) editions as these advances in knowledge and practice become available.

A limited number of printed copies of HEC-17 have been sent to Hydraulic and Drainage engineers in State DOT and FHWA offices.

To assist a wider audience, HIBS has posted HEC-17 on our website; now available for downloading at FHWA Hydraulics. Additionally, FHWA anticipates several future outreach efforts, including a presentation at the 2016 National Hydraulic Engineering Conference in Portland, Oregon, on August 11, 2016.

If you have any questions, please feel free to contact Joe Krolak at (202) 366-4611 (Joe.Krolak@dot.gov) or Brian Beucler, Office of Bridges and Structures at (202) 366-4598 (Brian.Beucler@dot.gov).

cc: FHWA Hydraulics Discipline Team
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16. Abstract

This manual provides technical guidance and methods for assessing the vulnerability of transportation facilities to extreme events and climate change in riverine environments. The focus is quantifying exposure to extreme flood events considering climate change and other sources of nonstationarity. It is anticipated that there will be multiple uses for this guidance including risk and vulnerability assessments, planning activities, and design procedure development.

The manual provides an overview of federal policies affecting floodplains and floodplain development including FHWA and FEMA policies as they affect transportation. It also provides a description of extreme and other flood events and provides an overview of the rainfall/runoff and statistical models designers use for hydrologic design. The manual also discusses the uncertainty associated with hydrologic models.

With a view toward future design, the manual explains the concept of nonstationarity and two important drivers for nonstationarity: climate change and land use/land cover changes. The manual introduces several tools for identifying and adjusting for trends in the historical record, as well as techniques for projecting floods. The manual provides an overview of climate modeling including descriptions of global climate models (GCMs), regional climate models (RCMs), statistical downscaling, and emissions scenarios.

To provide guidance to planners and engineers who plan, design, and maintain the nation's transportation infrastructure, the manual establishes a context based on the principles of risk and resilience. The manual describes the probabilistic nature of flood events and describes a larger assessment framework to provide cost-effective transportation assets.

The manual provides an analysis framework and specific guidance for addressing nonstationarity, including climate change, based on five levels of analysis. The guidance recognizes that all plans and projects do not merit the same attention. Finally, the manual provides case studies to illustrate several of the concepts included in the manual.

17. Key Words Extreme flood events, risk, resilience, floodplain, model uncertainty, data uncertainty, confidence limits, climate change, nonstationarity, hydrology, vulnerability, adaptation, highways, bridges, culverts, flooding, riverine, rainfall/runoff models, statistical models.		18. Distribution Statement No restrictions.	
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Kilgore Consulting and Management (Roger Kilgore) was the prime consultant developing this manual. Michael Baker International (Wilbert O. Thomas, Jr.), Thompson Hydrologics (David Thompson), and Desert Sky Engineering (Rudy Herrmann) were integral members of the consulting team. The FHWA team of Khalid Mohamed (COR), Joe Krolak (task monitor and technical panel chair), Cynthia Nurmi, Brian Beucler, Robert Kafalenos, and Robert Hyman directed the development of this manual.

We would also like to acknowledge the authors of the first edition of HEC-17: M.L. Corry, J.S. Jones, and P.L. Thompson. Each was with the FHWA at the time of publication.

The development of this manual included input from a one-day, peer exchange with invited climate scientists and engineers. The authors sincerely appreciate the participation of the following professionals: Chris Weaver (USEPA), Karen Metchis (USEPA), Jeff Arnold (USACE), Tim Cohn (USGS), Kate White (USACE), Robert Hirsch (USGS), and Robert Mason (USGS). The contents of this manual do not necessarily constitute their (or their agencies) endorsement of the information or approaches.

DISCLAIMER

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Glossary

ADAPTATION: Preparing for the effects of extreme events and climate change on the transportation infrastructure and systems. Adaptation refers to the planning, designing, constructing, operating, or maintaining transportation infrastructure while incorporating consideration of extreme events and climate change.

ADAPTIVE CAPACITY: The degree to which the system containing the asset (road, bridge, etc.) can adjust or mitigate the potential for damage or service interruption by climatic hazards.

ANNUAL EXCEEDANCE PROBABILITY (AEP): The probability that the magnitude of the random variable (e.g. annual maximum flood peak) will be equaled or exceeded each year.

BANKFULL: Water level in a stream corresponding to where water is flowing within the banks just before it spills out into the floodplain.

BASE FLOOD: The flood having a 1 percent chance of being equaled or exceeded in any given year.

BASE FLOODPLAIN: The area subject to flooding by the base flood.

BASE FLOW: Instream flow not directly caused by surface runoff.

CLIMATE: The characteristic weather of a region, particularly regarding temperature and precipitation, averaged over some significant interval of time (minimum 20 years).

CLIMATE CHANGE: 1) A significant and lasting shift in the statistical distribution of weather patterns around the average conditions (e.g., more or fewer extreme weather events) over periods ranging from decades to millions of years. 2) Any significant shift in the measures of climate lasting for an extended period of time, including major alterations in temperature, precipitation, coastal storms, or wind patterns, among others, that occur over several decades or longer. 3) A non-random shift in climate that is measured over several decades or longer. The change may result from natural or human-induced causes.

CONFIDENCE INTERVAL: A statistical concept linking the estimated value of a variable with the probability of the estimate being true. A confidence interval is bounded by the corresponding lower and upper confidence limits.

CONFIDENCE LIMITS: Statistical limits that define an interval in which the true value of a statistic is expected to lie with the stated probability.

DESIGN FLOOD: The peak discharge, volume (if appropriate), stage or wave crest elevation of the flood associated with the annual exceedance probability selected for the design of a highway asset.

DISCHARGE: Volume of water passing a given point per unit time. Also known as flow.

EXPOSURE: The frequency, nature, and degree to which a transportation asset (road, bridge, etc.) will experience a climatic hazard.

EXTREME EVENT: Severe and rare natural occurrence that may pose significant risks for damage, destruction, or loss of life. Per Order 5520 and for the purposes of this manual “extreme event” refers to risks posed by climate change and extreme weather events (FHWA 2014).

EXTREME FLOOD EVENT: Specific type of extreme weather event that is manifested as flooding.

EXTREME WEATHER EVENT: Significant anomalies in temperature, precipitation, and winds that may manifest as heavy precipitation and flooding, heatwaves, drought, wildfires, and windstorms (including tornados and tropical storms). They are rarely occurring, weather-induced events that usually cause damage, destruction, or severe economic loss

FLOOD: A general and temporary condition of partial or complete inundation of normally dry land areas resulting from the overflow of inland or tidal waters.

FLOOD FREQUENCY CURVE: A curve relating a range of flood flows with their respective annual exceedance probabilities (frequencies).

FLOODPLAIN: The land area susceptible to being inundated by flood waters.

FLOW: Volume of water passing a given point per unit time. Also known as discharge.

FREEBOARD: Vertical distance above a design water-surface elevation that provides a safety factor for waves, surges, drift, uncertainty in hydrologic estimates, and other contingencies.

HAZARD: Something that is potentially dangerous or harmful, often the root cause of an unwanted outcome.

HYDROGRAPH: Time series of flow (discharge) or stage at a particular location in a watershed.

HYETOGRAPH: Time series of rainfall, which can be expressed as intensity (rate), depth per incremental time unit, or total (accumulated) rainfall from the beginning of the storm (mass hyetograph).

HYDROLOGY: The earth science that considers the occurrence, distribution, and movement of water in the atmosphere, between the atmosphere and the earth's surface, and in the Earth.

HYDRAULICS: The applied science and engineering of the mechanical properties of water.

NONSTATIONARITY: A characteristic of time series data such that the data are heterogeneous. Trends over time prevent historical data from being used to estimate future conditions.

PRECIPITATION: Water in the form of rain, hail, sleet, or snow that forms in the atmosphere and falls to the earth’s surface.

RESILIENCE: The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.

RETURN PERIOD: The average length of time between occurrences in which the value of a random variable (e.g. flood magnitude) is equaled or exceeded. Actual times between occurrences may be longer or shorter, but the return period represents the average interval. The return period is the inverse of the Annual Exceedance Probability (AEP). For example, if the AEP equals 0.01 (or one percent) the return period is 100 years.

RISK: The consequences associated with hazards (including climatic) considering the probabilities of those hazards. More specifically for this manual, risks are the consequences associated with the probability of flooding attributable to an encroachment. It shall include the potential for property loss and hazard to life during the service life of the highway (23 CFR 650 A).

RUNOFF: The portion of a rainfall event discharged from a watershed into the stream network during and immediately following the rainfall.

SENSITIVITY: The degree to which an asset is damaged or service is interrupted by a climatic hazard.

STANDARD ERROR: A measure of the sampling variation of a statistic.

STATIONARITY: A characteristic of time series data such that the data are homogeneous. There are no trends that would prevent historical data from being used to estimate future conditions.

VULNERABILITY: The extent to which a transportation asset is susceptible to sustaining damage from hazards (including climatic). Vulnerability is a function of exposure, sensitivity, and adaptive capacity.

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List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
AEP	Annual Exceedance Probability
ARRM	Asynchronous Regional Regression Model
ASCE	American Society of Civil Engineers
BCCA	Bias-Correction Constructed Analogues
BCSD	Bias Corrected Spatially Downscaled
AEP	Annual Exceedance Probability
CISA	Climate-Informed Science Approach
CO_2	Carbon Dioxide
DCHP	Downscaled Climate and Hydrology Projections
EO	Executive Order
FEMA	Federal Emergency Management Agency
FFRMS	Federal Flood Risk Management Standard
FHWA	Federal Highway Administration
FIRM	Flood Insurance Rate Map
GIS	Geographic Information System
GCM	Global Climate Model (or General Circulation Model)
GHG	Greenhouse Gases
HCDN	Hydro Climatic Data Network
HDS	Hydraulic Design Series
HEC	Hydraulic Engineering Circular
IDF	Intensity-Duration-Frequency
IPCC	Intergovernmental Panel on Climate Change
LULC	Land Use/Land Cover
MAP-21	The Moving Ahead for Progress in the 21^{st} Century Act
MitFLG	Mitigation Framework Leadership Group
NOAA	National Oceanic and Atmospheric Administration
NFIP	National Flood Insurance Program
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NWS	National Weather Service

RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SCS	Soil Conservation Service (now the NRCS)
SRES	Special Report on Emission Scenarios
USACE	US Army Corps of Engineers
USGS	United States Geological Survey
WRC	Water Resources Council

Chapter 1. Introduction

Within the hydrologic cycle, the riverine environment consists of waterways, rivers, streams, lakes, wetlands, and other natural water resources conveying water. The riverine environment encompasses perennial waters (i.e., flowing all year round); intermittent (or seasonal waters); and ephemeral waters (generally flowing only after a precipitation event). The riverine environment also includes floodplains (i.e., land areas susceptible to a general and temporary condition of partial or complete inundation of normally dry land areas resulting from the overflow of inland waters). There are situations where rivers and streams flow into coastal waters or coastal waters otherwise influence the riverine environment. However, this manual does not address these coastal and riverine environment interactions.

The enormous breadth of the U.S. riverine environment results in ubiquitous interactions with transportation systems and infrastructure. In 1808, Treasury Secretary Albert Gallatin proposed a series of roadways to link the young nation. While historians note that the subsequent 1800's were primarily a period of railroad (and steamship) transportation, these drove the planning, design, construction, and operation of bridges, culverts, and other hydraulic appurtenances within the riverine environment. The 1892 establishment of the U.S. Office of Road Inquiry, followed by the 1915 establishment of the U.S. Bureau of Public Roads (BPR), illustrated an increasing federal role in highway transportation commensurate with use of private automobiles and development of riverine watersheds.

More recently, development in our riverine floodplains combined with potential changes in frequency and severity of storms and floods that might result from a changing climate are driving the need to improve our approaches for the planning, design, and operation of transportation infrastructure. Fiscally constrained state and federal budgets for infrastructure conflict with publically financed projects seeking to — or being required to — address climate change and extreme events in the design of hydraulic structures. Therefore, there is a significant need for the Federal Highway Administration (FHWA) to provide updated and expanded guidance on risk assessment methods, techniques for estimating extreme events (including the effects of climate change), and management strategies for floodplain development. This manual, Hydraulic Engineering Circular number 17 (HEC-17), fills that gap.

FHWA developed this guidance manual to support project delivery areas such as planning, design, maintenance, and operations involved with highway networks within riverine environments. As appropriate, this manual can supplement other FHWA technical guidance in all project delivery areas. FHWA believes that this manual contains appropriate and actionable hydrologic guidance on floodplains, extreme flooding events, climate change, risk, resilience, and uncertainty. The primary audiences for this manual are those agencies and individuals who have direct responsibility for the ***design*** of roadway infrastructure and include hydrologists, hydraulic engineers, civil engineers, and roadway designers. FHWA intends that the manual be useful for those who ***plan***, ***build***, and ***maintain*** our roadways including planners, field inspectors, construction supervisors, and maintenance personnel. Although the technical components of this manual might be outside the discipline specialties of some readers, the overlying intent and justification for the approaches contained herein should be understandable to a wide cross-section of readers with varying backgrounds and expertise.

This second edition of HEC-17 supersedes the first edition published in 1981. The first edition focused on the use of risk analysis to design encroachments in the floodplain. While there remain some important approaches and concepts within the first edition, this second edition expands significantly on the scope of the guidance including broader discussion of risk analysis while adding guidance on extreme events, resilience, climate change, and uncertainty.

1.1. Purpose and Scope

FHWA intends this manual to provide technical guidance grounded in the best available and actionable engineering and scientific data and approaches with a framework that is adaptable to future improvements. FHWA understands that the rapid pace of research and application may perhaps make some of the contents “dated” as the state of practice advances. However, this manual aligns with FHWA efforts to implement larger federal and other efforts on climate informed science approaches (CISA). FHWA purposely excluded some data and methods that do not meet its standards of “best available” and “actionable.”

FHWA anticipates that there will be multiple uses for this information, including risk and vulnerability assessments, planning activities, and design. When using this manual, FHWA believes planners and designers conducting such activities may see more cost-effective use of transportation resources, especially when considering the entire project lifecycle service benefits and costs. As discussed within this manual, FHWA further believes that incorporating the potential effects of extreme events and climate change on flooding and designing our transportation system for more resilience when exposed to **extreme flood** events may enhance the lifecycle benefits.

The focus of this manual is on describing ***exposure*** to extreme riverine flooding in the context of changing conditions. The manual specifically addresses climate change as one source of change that potentially affects the magnitude and frequency of extreme events that, in turn, may affect transportation assets.

Extreme flooding is one manifestation of ***extreme weather***. The term extreme weather includes severe or unseasonable weather, heavy precipitation, storm surge, flooding, drought, windstorms (including hurricanes, tornadoes, and associated storm surges), extreme heat, and extreme cold. FHWA describes extreme weather events as rarely occurring, weather-induced events that usually cause damage, destruction, or severe economic loss (FHWA 2012a).

Hydrologic designers characterize flood events by their annual exceedance probability (AEP). For example, the flood with a one percent AEP has a magnitude that has a one percent chance of being equaled or exceeded each year. Flood events used for design of most transportation assets range from the 10 percent annual exceedance probability (AEP) to 0.2 percent AEP. For some types of assets and situations, designers may use design events outside of this range. The choice of design events influences resilience to extreme events. To foster clear communications between design professionals, climate scientists, and the public, a common definition of “extreme” will be useful. This manual addresses this communication in several places.

FHWA considers ***exposure*** of transportation assets to extreme events and climate change a component of vulnerability. FHWA defines ***vulnerability*** as the extent to which a transportation asset is susceptible to sustaining damage from climatic hazards. Figure 1.1 describes vulnerability as a function of three components: ***exposure***, ***sensitivity***, and ***adaptive capacity*** (FHWA 2012b).

The transportation assets of primary focus in the development of this manual are bridges and culverts. This manual does not address storm drains and stormwater management ponds, although some topics contained herein might apply to these other classes of transportation assets.

As appropriate, this manual will address both existing and new (proposed) transportation assets. Development of proposed assets offers the flexibility to incorporate new information on climate change and design methods immediately during planning and design. Owners may screen existing assets to assess their vulnerability to climatic hazards and, when appropriate, define, plan, design, and implement adaptation measures.

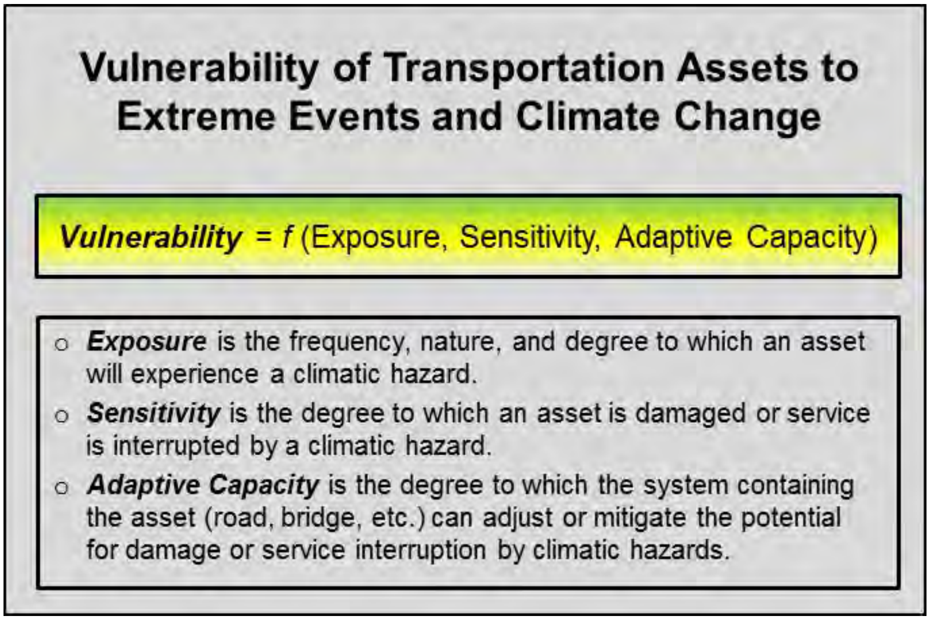

Figure 1.1. Vulnerability of transportation assets.

1.2. Organization

FHWA organized this manual into eight chapters. The manual also includes a glossary, list of acronyms, reference section, and appendices. ***Chapter 1***, this chapter, provides discussion of the purpose and scope, organization, units, and related guidance.

Floodplain development policies and decisions affect the overall exposure of transportation assets to extreme events, particularly flooding. Federal policy, regulations, and guidance, as well as good engineering judgement regarding the location and design in floodplains contribute to the frequency, nature, and degree to which an asset experiences flooding over its lifetime. Therefore, ***Chapter 2*** provides discussion of federal policies regarding transportation infrastructure built in or near floodplains. The chapter starts with a national overview; then focuses on FHWA policy and guidance; followed by FEMA policy and guidance as they affect transportation infrastructure.

Assessment of exposure requires useful tools and data. ***Chapter 3*** provides guidance on the methods and issues associated with estimating flood flows for planning and design. The chapter highlights the implications for linking the temporal and spatial scales of the tools that designers use for estimating flood flows with those that climate models can produce. This chapter also highlights how uncertainty influences the tools designers use and describes the need to embrace uncertainty in both data and methods. Uncertainty has always been a reality in the hydrologic and hydraulic design of bridges and culverts, but planners and designers have not always recognized it appropriately.

Chapter 4 provides discussion of flood nonstationarity and its importance in estimating flood flows. The chapter describes potential causes of nonstationarity, particularly, climate and land use changes, as well as methods for identifying and adjusting for trends. The chapter also includes description of climate change as it relates to trends in flood flows. A final section covers projecting flood frequency under conditions of nonstationarity.

Chapter 5 addresses climate modeling and its relevance for estimating extreme flows. The chapter discusses climate modeling, downscaling, and emissions scenarios to provide the planner and engineer with an understanding of the resources and methods available for incorporating climate change in transportation planning and infrastructure design.

Chapter 6 explores risk and resilience. ***Risk*** provides an overall framework for assessing or analyzing planning and design strategies and decisions. Risk analysis or assessment incorporates the concept of vulnerability and provides some measure of the costs (monetary and other) associated with damages and performance interruptions to facilitate the comparison of alternatives. This chapter also discusses how planners and designers can reduce the vulnerability of transportation assets by improving the asset/system resilience. ***Resilience*** is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions caused by hazards.

Chapter 7 describes a framework for assessing or analyzing risk and resilience in floodplain development and management and hydrologic design. Recognizing that not all sites and projects require the same tools and data, the chapter includes a discussion on a range of levels of analysis that planners and designers can tailor for a specific project. The chapter also includes a brief section on current knowledge gaps.

Finally, ***Chapter 8*** provides a series of case studies. These cases studies serve a variety of purposes including illustrating example applications of the concepts and methods discussed in this manual. The case study discussions highlight the beneficial accomplishments and identify potential methodological improvements.

1.3. Units of this Manual

This manual uses customary (English) units consistent with FHWA policy. However, in limited situations, both customary (English) units and SI (metric) units are used or only SI units are used because these are the predominant measure used nationwide and globally for such topics. In these situations, the manual provides the rationale for the use of units. Appendix A provides information on units and unit conversions.

1.4. Related Guidance

This manual meets a specific need for guidance related to floodplains, extreme events, risk, and resilience in the riverine environment. However, it does not attempt to reproduce or replace other important guidance manuals and documents.

HDS 2 "Highway Hydrology" provides detailed explanations for many of the hydrologic techniques discussed in this guidance (McCuen *et al.* 2002). HDS 2 provides in-depth information on the selection and application of peak flow methods for ungaged watersheds, the analysis of stream gage data, hydrograph methods, and several other topics.

The FHWA manual that addresses transportation design in the coastal environment is Hydraulic Engineering Circular (HEC): **"Highways in the Coastal Environment," HEC-25 (HEC-25)** Douglass and Krolak 2008). That primary technical manual provides general guidance for the analysis, planning, design, and operation of highways in the coastal environment. HEC-25 presents some of the physical coastal science concepts and modeling tools that the coastal engineering community has developed that is applicable to highways.

HEC-25 Volume 2 (Douglass *et al.* 2014) supplements the primary HEC-25 manual by recommending specific approaches for modeling and mapping storm surge and waves caused by extreme events under various climate change scenarios. Volume 2 presents specific possible (i.e. projected) climate change scenarios, primarily in terms of sea level rise scenarios.

"Climate Change and Extreme Weather Vulnerability Assessment Framework," FHWA-HEP-13-005 FHWA (2012b) presents guidance on an overall "framework" for planning studies to assess the vulnerability of transportation facilities to climate change and extreme weather events. This manual presents guidance for assessing vulnerability at the asset or larger scale within that overall framework.

Finally, FHWA maintains two websites that provide current and evolving guidance and research information:

- hydrology and hydraulics: http://www.fhwa.dot.gov/engineering/hydraulics/index.cfm, and
- climate adaptation: http://www.fhwa.dot.gov/environment/climate_change/adaptation/.

Because both of these areas benefit from active research and development programs, FHWA highly recommends periodically checking these websites for new resources.

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Chapter 2. Floodplains and Federal Policies for Development

Federal floodplain policy provides the broad goals and limitations within which the U.S. conducts scientific, planning, and engineering activities. This chapter summarizes the relevant statutes, regulations, executive orders, and guidance that shape federal floodplain policy. First, the chapter provides a national overview. Following this are sections describing policy from the two primary agencies affecting the transportation infrastructure: FHWA and FEMA.

2.1. National Overview: Evolving Recognition of Flood Risks

Floods and flood risks have affected U.S. highways even before the 1915 creation of the Bureau of Public Roads. Literature suggests that from 1900 to 1937 floods caused roughly 9,000 highway bridges failures (White 1945). Floods occurring between December 1935 and April 1936 resulted in loss of 911 highway bridges alone (White 1945).

Prior to 1936, there was no national flood-control program. The Flood Control Act of 1936 and the Watershed Protection and Flood Prevention Act of 1954 authorized the U.S. Army Corps of Engineers (USACE) and Soil Conservation Service (SCS) to build flood control projects to reduce flood damages. The Bureau of Public Roads (BPR), recognizing the risks associated with flooding and changing land use conditions, required the (then) new Interstate system to use the following standard (BPR 1956):

> *"Designs for all culverts and bridges over streams shall … accommodate floods at least as great as that for a 50-year frequency or the greatest flood of record, whichever is the greater, with the runoff based on the land development expected in the watershed 20 years hence and with backwater limited to an amount which will not result in damage to upstream property or to the highway."*

However, even with a large investment in flood protection and prevention projects, flood damages continued to increase. Currently, federal law provides for a FHWA emergency relief program with an annual budget of $100,000,000 (Title 23, Section 125(c)(2)(A)). In reality, over the last two decades, FHWA estimates providing $700,000,000 annually in emergency relief with the majority of those annual funds targeted to floods (Wolf 2016). For the entire U.S., the National Weather Service estimates that the 30-year average annual flood losses (through 2014) are $8 billion in damages (NWS 2015). With this growing recognition of the costs and implications, federal floodplain policy has evolved. Figure 2.1 provides a summary of the periods and highlights in policy development discussed in subsequent sections of this manual.

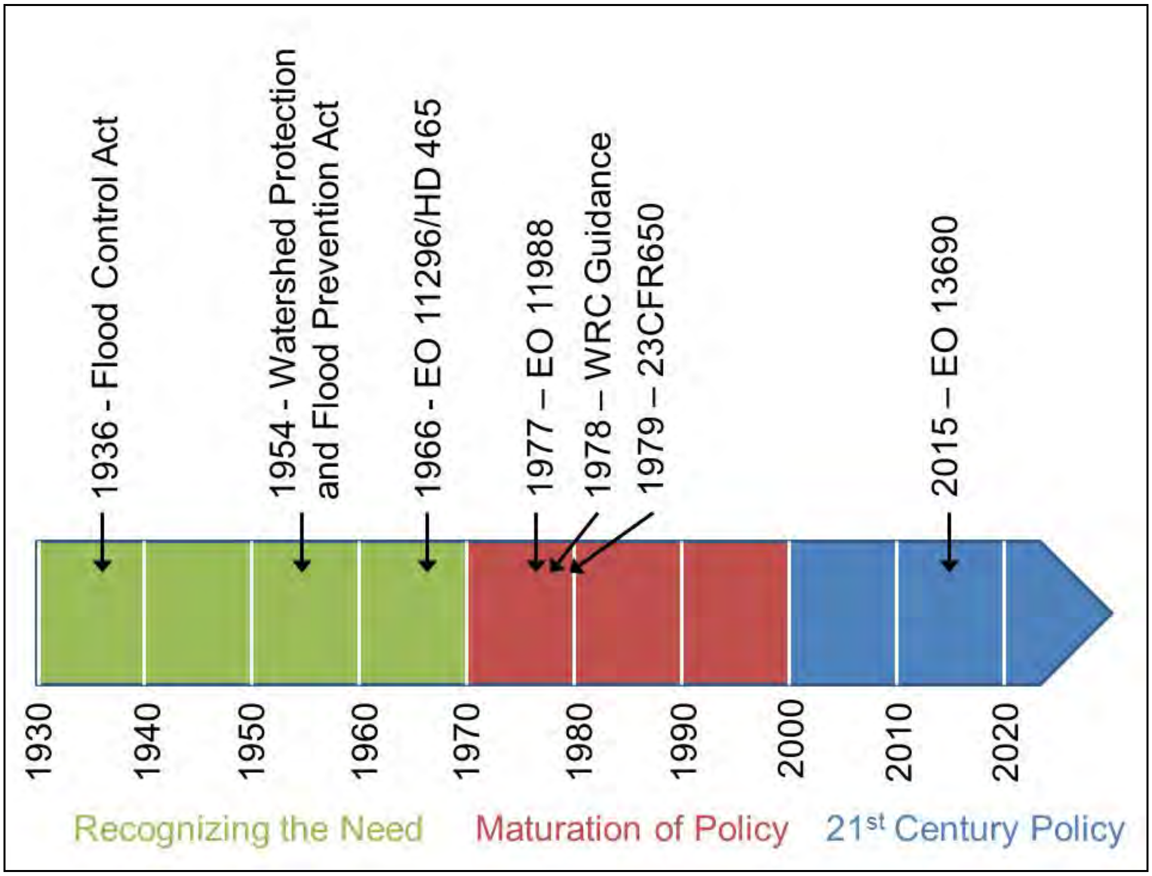


Figure 2.1. Timeline for national floodplains policy.

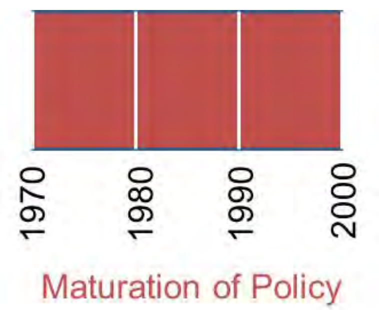
2.1.1. Recognizing the Need for Floodplain Management

In addition to BPR, USACE, and SCS, many federal agencies adopted some type of flood management approach or policy. However, such efforts varied widely in scope and focus. Additionally, federal leadership recognized increasing U.S. flood losses. As a consequence, on August 10, 1966, President Johnson transmitted to Congress House Document (HD) 465 "A Unified National Program for Managing Flood Losses." HD 465 was the beginning of a coordinated national floodplain management program in the United States to reduce flood losses and provided Congress with a report prepared by the Task Force on Federal Flood Control Policy (Task Force on Federal Flood Control Policy 1966).

The Task Force argued for the use of nonstructural and structural approaches to reduce flood losses. The recommendations of HD 465 included the development of uniform national flood frequency guidelines, establishment of a federal flood insurance program, and recommended that federal agencies carry out flood hazard evaluations before taking actions in a floodplain.

On August 10, 1966, simultaneously with release of HD 465, President Johnson issued Executive Order (EO) 11296 "Evaluation of Flood Hazard in Locating Federally Owned or Financed Building, Roads, and Other Facilities, and in Disposing of Federal Lands and Properties" (Executive Order No. 11296 1966). EO 11296 required executive agencies of the federal government to provide leadership in encouraging an effort to prevent uneconomic use and development of floodplains and to lessen the risk of flood losses in connection with federal lands and installations and federally financed or supported improvements.

2.1.2. Maturation of Federal Floodplain Policy



Federal agencies approached and implemented EO 11296 in different and sometimes inconsistent ways. On May 24, 1977, President Carter issued EO 11988 “Floodplain Management” to remedy these variations and improve floodplain management. EO 11988 required federal agencies to take a more active role in support of floodplain management and to reduce flood losses (Executive Order No. 11988 1977). EO 11988 superseded and greatly expanded EO 11296. EO 11988 provided additional guidance on floodplain management and required that each federal agency provide leadership and take action to reduce the risk of flood loss to minimize the impacts of floods on human safety, health, and welfare, and to restore and preserve the natural and beneficial values served by floodplains. In issuing EO 11988, President Carter revoked EO 11296.

As described in EO 11988, each agency had the responsibility to evaluate potential effects of any action it may take in a floodplain and ensure that planning, programs, and budget requests reflect consideration of flood hazards and floodplain management.

EOs have their specific legal authority. Beyond that legal authority, EO 11988 also relied on the authority and provisions within the National Environmental Policy Act of 1969 (NEPA), the National Flood Insurance Act of 1968, and the Flood Disaster Protection Act of 1973.

Within the transportation community, the NEPA based requirements of the EO are an important and intertwined facet in EO 11988 implementation, including program and project delivery. Floodplain managers, regulators, or others not typically involved in project delivery often do not recognize such intertwined alignment. As an example of NEPA alignment, EO 11988 requires that before taking applicable actions, each agency must determine whether the proposed action will occur in a floodplain and evaluate the impacts of those actions within NEPA associated documentation (e.g., categorical exclusions, environmental assessments, or environmental impact statements). Other examples include provisions for each agency to provide an opportunity for early public review of any plans or proposals for actions in floodplains and avoiding direct or indirect support of floodplain development whenever there is a practicable alternative.

EO 11988 contains concepts aligned with floodplain management approaches and legal imperatives. For example, an agency needed to evaluate the flood hazards by consulting the Department of Housing and Urban Development (HUD) floodplain maps, if available. (These floodplain maps are now called “Flood Insurance Rate Maps” and are administered by FEMA). If such maps were not available, the agency needed to determine the location of the floodplain based on the best available data. EO 11988 defined “floodplain” as that area subject to a 1-percent chance of flooding in any given year.

Additional floodplain management portions of EO 11988 require that construction of federal structures and facilities in the floodplain must be in accordance with the standards and criteria consistent with the intent of those under the National Flood Insurance Program (NFIP).

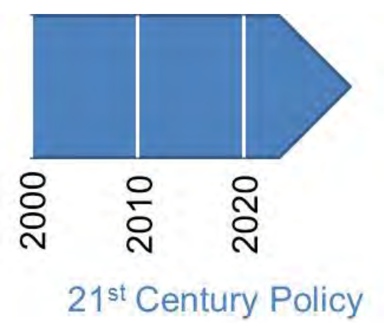
To ensure that federal agencies formally implemented the EO, provisions gave them one year to issue or amend regulations and procedures to ensure compliance. The regulations and procedures recommended the “… means that the agency will employ to pursue the nonhazardous use of riverine, coastal and other floodplains in connection with the activities under its authority."

Additionally, EO 11988 required agency consultation with White House affiliated groups such as the Water Resources Council (WRC) and the Council for Environmental Quality (CEQ) to ensure adequate agency implementation. Together with these and other provisions, EO 11988 represented a milestone in federal floodplain policy and direction.

In 1978, WRC issued guidance "Floodplain Management Guidelines for Implementing EO 11988" that provided agencies with consistent guidance for implementing EO 11988. The WRC report (1978) acknowledged that the Nation's floodplains are the scene of: 1) unacceptable and increasing flood losses and 2) degradation of the natural and beneficial values of floodplains.

Later sections of this chapter discuss the approach taken by USDOT and FHWA implementing EO 11988. EO 11988 essentially changed and unified the manner in which federal agencies addressed floodplain management.

2.1.3. 21st Century Floodplain Policy Risks and Challenges



In the first years of the 21st Century, hurricanes and other major hazard events resulted in large increases in flood losses. Additionally, there were concerns that some of these extreme events were indicative of - or precursors to - even more hazardous conditions in the future. President Obama issued several EOs that sought to focus and characterize the related risks of these types of extreme events.

After Hurricane Sandy in 2012, President Obama established the Mitigation Framework Leadership Group (MitFLG), comprised of representatives of all federal departments and major agencies. MitFLG operates under the auspices of the National Security Council in support of and consistent with the National Preparedness Goal, Presidential Policy Directive-8 (PPD-8) and the Post Katrina Emergency Management Reform Act (including 6 U.S.C. §313, 314, 321, and 743). From 2013 to 2015, MitFLG developed a Federal Flood Risk Management Standard (FFRMS).

FFRMS considers future climate conditions in an effort to reduce the risk and cost of future floods on federal investments. MitFLG intended that FFRMS would create a national minimum flood risk management standard to ensure that federal actions located in or near the floodplain consider risks, changes in climate, and vulnerability. The FFRMS encourages use of natural features and nature-based approaches (generally known as "green infrastructure") in the development of alternatives for federal actions. Most significantly, FFRMS provides for an expanded floodplain to address current and future flood risks. To achieve this, FFRMS proposed that actions use one of the following approaches in to identify areas subject to flooding:

1. apply the elevation and flood hazard area resulting from a climate-informed science approach (CISA) using the best-available, actionable hydrologic and hydraulic data and methods that integrate current and future changes in flooding based on climate science;
2. apply the elevation and flood hazard area that result from using the elevation determined by adding 2 feet of freeboard to the base (1-percent chance or 100-year) flood elevation for non-critical actions and by adding 3 feet of freeboard to the base (1-percent chance or 100-year) flood elevation for critical actions; or

3. apply the elevation and flood hazard area subject to flooding by the 0.2-percent chance (500-year) flood.

FFRMS states a preference for the climate-informed science approach. The reason for this preference is that the other two approaches are essentially surrogates for applying extreme event considerations. Importantly, the FFRMS provides each agency with the ability to decide which approach or approaches they wish to implement on a project-by-project basis.

On January 30, 2015, President Obama issued EO 13690 “Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input” (Executive Order 13690 2015). EO 13690 (i) amended the 1977 EO 11988 on Floodplain Management; (ii) instituted the FFRMS; and (iii) set up a process to seek public input on associated updates to the February 1978 Guidelines for Implementing Executive Order 11988 (Guidelines). EO 13690 replaced EO 11988’s base (1-percent chance) flood elevation with the FFRMS approaches. The White House tasked MitFLG to update the Guidelines to aid agencies with implementing EO 11988, as amended. EO 13690 also required agencies to develop a plan containing broad milestones and timeframes to implement the new requirements (implementation plan). For example, in summer of 2015, USDOT (including FHWA) provided the White House with their implementation plan, obtaining White House approval in August 2015.

After months of responding to and resolving public and agency comments, MitFLG provided updated Guidelines to the Water Resources Council. On October 8, 2015, the Water Resources Council published final updated Guidelines. After approval and publication of the Guidelines, EO 13690 required agencies to move forward on activities described in their implementation plan.

EO 13690 is not a self-implementing requirement. As described in the implementation plan, USDOT and FHWA are required to take actions to update their procedures before they apply to FHWA projects. With the issuance of the Water Resources Council Implementing Guidelines in 2015, USDOT and FHWA are in a better position to pursue amendments to their current floodplain requirements to reflect EO 13690 and the amended EO 11988. However, no FHWA program should deviate from the existing requirements of 23 CFR 650 Subpart A “Location and Hydraulic Design of Encroachments on Flood Plains” until FHWA develops new/revised regulation, policies, and guidance.

2.2. FHWA Regulations, Policy, and Guidance

FHWA’s regulations, policies, and guidance implement EO 11988 national floodplain goals and requirements while keeping public safety paramount and balancing flood risks, environmental stewardship, and cost in the planning, design, construction, and operations/maintenance of transportation infrastructure.

2.2.1. Highways and Floodplains

FHWA has long recognized the risks of locating highways in floodplains. Through PPM 20-4, FHWA applied flood management standards to Interstates. In response to EO 11296, the BPR Director F.C. Turner issued guidance in Instructional Memorandum 20-1-67 (32-44) (Turner 1967). The memorandum advised:

> *“In planning the location of a highway, serious consideration should be given to locations that avoid areas subject to flooding. If an encroachment of a floodplain is necessary, an evaluation should be made of the flood potential, the effect of the flood potential on the highway and the effect of highway construction on the flood hazard.”*

On October 10, 1974, FHWA codified its floodplain requirements using regulation 23 CFR 650 Subpart A “Location and Hydraulic Design of Encroachments on Flood Plains” (23 CFR 650 A). The policy of the FHWA was to encourage a broad and unified effort to prevent uneconomic, hazardous, or unnecessary use and development of the Nation's flood plains, and in particular, to lessen the risk of flood losses in connection with improvements financed with federal funding. The regulation also sought to ensure that highway locations avoid areas subject to flooding and comply with the WRC May 1972 publication "Flood Hazard Evaluation Guidelines for Federal Executive Agencies."

After issuance of EO 11988 in May 1977, FHWA worked under the auspices of USDOT to draft procedures to comply. As a result, on April 23, 1979 USDOT issued DOT Order 5650.2 “Floodplain Management and Protection.” DOT Order 5650.2 represented a departmental approach to ensure compliance. A majority of USDOT agencies (e.g., Federal Aviation Administration, Federal Transit Administration, Maritime Administration, etc.) incorporated DOT 5650.2 into their (NEPA affiliated) procedures. However, DOT 5650.2 also allowed a specific agency within USDOT to issue specific regulations.

FHWA did so by updating 23 CFR 650A. On November 26, 1979, FHWA issued the updated regulation codifying its policies and procedures for location and hydraulic design of highway encroachments in base (1-percent chance) floodplains. In this 1979 update, FHWA’s policies included avoiding longitudinal encroachments and significant encroachments, where practicable, minimizing impacts on base floodplains, and preserving and restoring base floodplain values. During NEPA associated compliance, the procedures require a location hydraulic study to identify the potential impact of the highway alternatives on the base floodplain. If an encroachment cannot avoid significant impacts to the base floodplain, then the NEPA documents would cite reasons and require approval from the FHWA Division Office. The procedures provide for minimum standards for interstate highways, set freeboard requirements to account for debris, and require state DOTs to establish design flow standards for hydraulic structures. Notably, the FHWA regulations, policies, and procedures apply to encroachments in all base floodplains, not just the floodplains regulated by FEMA in the National Flood Insurance Program (NFIP). Additionally, FHWA’s regulation incorporated a requirement for project-by-project risk assessments or analyses.

For technical guidance, FHWA drew upon the extensive series of technical guidance manuals and documents in the form of Hydraulic Engineering Circulars (HECs) and the Hydraulic Design Series (HDS). FHWA had developed many of these guidance documents starting in the 1960s, focusing on, for example, culvert hydraulics (HEC-5) or bridge waterway hydraulics (HDS 1). As a response to EO 11988 and 23 CFR 650A, FHWA created the first edition of HEC-17 “The Design of Encroachments on Flood Plains using Risk Analysis.” HEC-17, first edition, encouraged planners and designers to examine multiple flood events that would inform appropriate design. This may include the 50-year event, the 100-year event, the overtopping event, and/or the 500-year event. Together, the various HECs and HDSs encouraged practitioners to consider existing land use conditions as well as future land use conditions that may exist during the lifetime of the road or bridge. Moreover, the potential effects of change, including climate change, became increasingly relevant to FHWA hydrologic and hydraulic design.

2.2.2. Coordinating Highway Encroachments with FEMA

FHWA’s policies include requirements to be consistent with the Standards and Criteria in the NFIP, where appropriate. To assist state DOTs to comply with this policy, FHWA developed coordination procedures for Federal-aid highway projects with encroachments in NFIP regulated floodplains. The procedures address scenarios for encroachments in floodways, regulated floodplains that have a detailed design study, and regulated floodplains with approximate zones. FEMA agreed to these procedures by signing a Memorandum of Understanding with FHWA in 1982.

2.2.3. Response to Climate Change

To improve guidance on developing highways near or in a floodplain, FHWA has taken steps to address the potential effects of climate change in planning and design of highways:

- Issued a memorandum identifying the climate adaptation activities that are eligible for FHWA funding, including vulnerability assessments, as part of design and construction of projects or features to protect assets from damage associated with climate change (FHWA 2012a).
- Issued an FHWA Order 5520 committing the agency to integrating climate risk considerations into the delivery and stewardship of FHWA programs (FHWA 2014). See Appendix C for full text.
- Updated FHWA's emergency relief program guidance to reflect climate resilience.
- Implemented the 2012 MAP-21 legislation (P.L. 112-141) requiring states to develop risk-based asset management plans and to consider alternatives for facilities repeatedly needing repair or replacement with federal funding.
- Developed tools and guidance for systematic consideration of climate risks at transportation systems.
- Completed pilot studies to better understand climate change effects on transportation infrastructure and to identify potential adaptation strategies.

FHWA produced this manual (HEC 17) to provide further guidance for incorporating climate change in evaluating flood risks, floodplain management, and resilience.

2.3. FEMA Regulations, Policy and Guidance

A part of the Federal Emergency Management Agency's (FEMA's) mission is to help the Nation prepare for, protect against, respond to, recover from, and mitigate flooding hazards. FEMA's role in regulation of floodplains addresses their mission elements of "protecting against" and "mitigating" flood hazards. Effective coordination with FEMA, when appropriate, is important for the planning, design, and implementation of transportation infrastructure and understanding their evolution regarding future land use and climate change.

FEMA's objectives for floodplain management are to reduce flood damages and prevent the loss of life by minimizing or excluding development in the floodplain. As defined by FEMA, the floodplain is the land area susceptible to inundation by water. At the beginning of the National Flood Insurance Program (NFIP) in 1968, the program adopted the 100-year flood as the standard or base flood for mapping floodplains in the United States. The area inundated by the 100-year flood determines the ***Special Flood Hazard Area*** (SFHA) on ***Flood Insurance Rate Maps*** (FIRMs) developed by FEMA and used to determine flood insurance rates for structures. FEMA deemed that the 100-year flood, or flood with a 1-percent annual exceedance probability, was appropriate because it represented a degree of risk and damage worth protecting against, while not imposing overly stringent requirements or the burden of excessive costs on property owners (FEMA 1983).

Figure 2.2 illustrates the concepts of the 100-year floodplain, the floodway, floodway fringe, and surcharge. The floodway is the portion of the floodplain that conveys most of the floodwaters.

Designation of a floodway allows for part of the floodplain to incur development while preserving the ability of the floodplain to convey flood discharges. Development can occur within the floodway fringe, which is the area outside of the floodway, but within the 100-year floodplain.

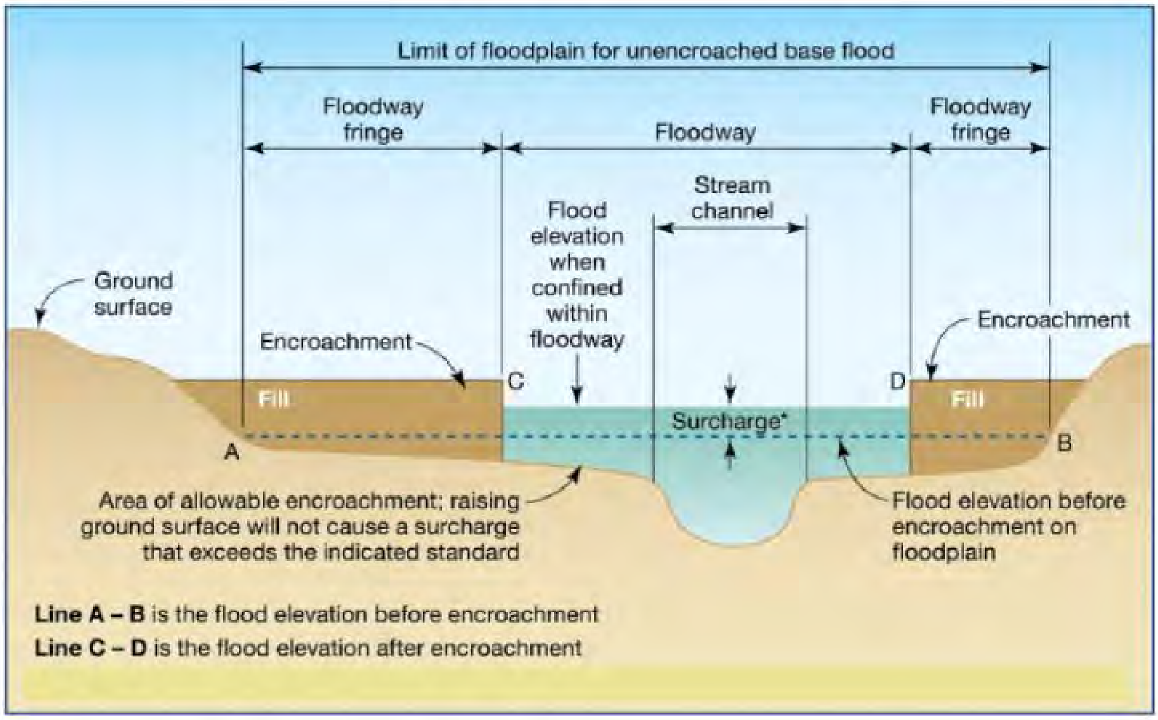


Figure 2.2. Example floodplain cross-section.

FEMA calls the increase in 100-year or base flood elevation from the “no floodway” to the “with floodway” condition a ***surcharge***. FEMA adopted a surcharge of one foot as the maximum increase allowable, though some communities and states have adopted more stringent standards. Once a community adopts a floodway, the community must prohibit development in that floodway unless engineering analyses demonstrate that there will be no increase in flood levels.

The local community with land use jurisdiction, whether it is a city, town, county, or state, has the responsibility for enforcing NFIP regulations in that community if the community is participating in the NFIP. Communities participating in the NFIP have adopted floodplain ordinances and may have established a permit requirement for development in the 100-year (base) floodplain. Where Flood Insurance Rate Maps are available, their use is mandatory for highway agencies in determining whether a highway location alternative will include an encroachment on the 100-year (base) floodplain. Therefore, understanding floodplain regulations is critical for implementation of effective plans and projects.

Chapter 3. Riverine Flood Events

The purpose of this chapter is to provide a summary of methods used to estimate riverine flood events. It begins with a discussion of floods and flood events, continues with summaries and assessments of methods for estimating flood discharges that are useful for transportation design, and then finishes with a discussion of extreme flood events.

3.1. Base Flow, Bankfull, and Floods

The terms ***base flow*** and ***bankfull*** are useful reference points for discussing floods. ***Base flow*** represents the long-term average discharge of a stream when the watershed is not immediately responding to rainfall events. That is, base flow comes from sources other than surface runoff. A runoff event occurs on a stream whenever the watershed responds to a precipitation event and causes an increase of stream discharge above base flow.

Precipitation can occur in the form of rain, hail, sleet, or snow. Watersheds respond more rapidly to rainfall compared with snowfall such that most larger runoff events result from rainfall. However, snowmelt with or without additional rainfall may also result in large runoff events. Rainfall over a watershed varies spatially and with time. A ***hyetograph*** refers to the time-intensity relationship for a rainfall event.

Watersheds respond to precipitation based on the hyetograph and the watershed characteristics. In general, more intense rainfall over a longer duration results in a greater watershed response in terms of ***runoff***. Some watershed characteristics, such as watershed size and slope, also influence the amount of runoff. Runoff is the portion of the rainfall event that discharges from the watershed into the stream network during and immediately following the rainfall. However, the watershed retains some of the rainfall as losses. These losses are a function of the watershed characteristics, such as plant interception, storage in small surface depressions, and infiltration into the soil.

Runoff moves over the surface of the watershed (hence it is called surface runoff) and collects in small streams. Runoff eventually collects in the main stream of the watershed and forms a time-rate curve called a ***hydrograph***.

For perennial streams (streams that always carry water), ***bankfull discharge*** is a relatively frequent watershed runoff event, usually more frequent than the two-year return interval (Leopold *et al.* 2005). When stage exceeds bankfull, the stream spreads onto the floodplain; greater inundation depths result from less frequent (higher magnitude) runoff events. Figure 3.1 shows an example of a river stage slightly above bankfull.

A ***flood*** is an event exceeding base flow where flows in a stream inundate normally dry land. Usually, flood flows exceed the stream channel confines and flow onto the floodplain. A flooding Pedernales River (August 17, 2007) in Texas is captured in the photograph in Figure 3.2 about 12 hours after 11 inches of rain fell in the area near Fredericksburg, Texas. Discharge rose from a base flow of 900 ft^3/s to 84,000 ft^3/s in approximately 12 hours.

Most commonly, the annual exceedance probability (AEP) or return period of a flood event refers only to the peak flow from the runoff hydrograph. The greater the peak flow, the lower the AEP and, conversely, the greater the return period. As may be inferred from Figure 3.2, the destructive power of floods comes from not only the peak discharge, but also the associated flow velocities and flood duration. The rate of rise before the peak discharge as well as the rate of decline after may also influence the effects of a flood.

Figure 3.1. Shire River in Malawi near bankfull stage.

Figure 3.2. Flooding on the Pedernales River, Texas.

For ephemeral streams (streams that are dry for substantial periods), years may pass between watershed runoff events. Associating an AEP or return period with a specific peak discharge in such cases is challenging, particularly for more frequent events such as bankfull discharge. Section 9.3.1 of HDS 2 (McCuen *et al.* 2002) describes several methods for addressing stream gage analysis at ephemeral streams.

3.2. Methods for Estimating Flood Discharge

As shown in Figure 3.3, FHWA classifies the technology for estimating flood discharge into two main categories: rainfall/runoff and statistical. For rainfall/runoff models, precipitation in the form of rain is a primary input. These models range from the very simple, such as the rational method, to very complex representations of many physical processes. These models may also be event-based or continuous simulation. Statistical models may also range from very basic to more complex, but rely on historical observations to estimate design flows.

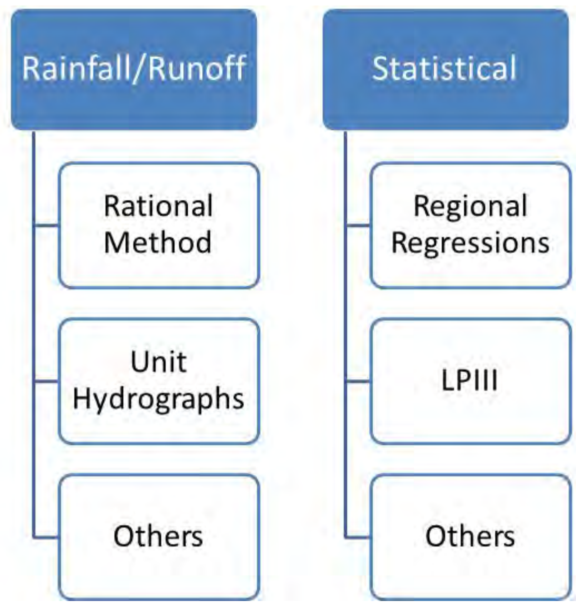


Figure 3.3. Hydrologic model types and examples.

This section provides an overview of representative common methods used for hydrologic analysis including those shown in the figure. The methods included are not intended to be exhaustive of all methods used for transportation (or other) design problems, but rather illustrative. A complete reference for hydrologic analysis for transportation design is HDS 2 (McCuen *et al.* 2002) and the reader is directed to that resource for additional information.

When using hydrologic tools - and to understand how they might be adapted for climate change - it is useful to classify the components of the methods as being either variables or parameters (Clarke 1973). A ***variable*** is a quantity that changes in the context of the estimating method. A ***parameter*** is considered to be constant or to have a constant value for a particular application. The primary variables used in hydrology are precipitation (depth or rate) and discharge (volumetric flow rate). The parameters used in hydrologic analyses differ and depend on the method used. For statistical methods, parameters generally include the statistical distribution parameters. Examples of statistical parameters are mean (average), variance (or standard deviation), and skew coefficient. For rainfall/runoff methods, parameters are model specific. For example, the rational method runoff coefficient is a parameter (although it is modified to represent the effect of expected land use changes on watershed response). The distinction between variables and parameters is also relevant for evaluating future changes such as those that may result from climate change; that is, might climate change simply affect model variables (data) or model parameters?

If an analysis requires only an estimate of peak discharge, then statistical methods are generally preferred because statistical methods are based on observations of watershed behavior. If stream gage data are not available, then rainfall/runoff methods, such as the rational method, hydrograph methods, and others, can be used to estimate watershed response. However, if a hydrograph is required, then the unit hydrograph approach is probably most appropriate. Designers should calibrate model parameters if measured rainfall and runoff data are available. If calibration data are not available, performing a sensitivity analysis is a good practice.

Designers can generate flood frequency curves using rainfall/runoff and statistical methods. The flood frequency curve summarizes the relationship between flood magnitude and its corresponding AEP for a given watershed. As shown in Figure 3.4, the AEP is usually represented on a probability scale with AEP (more rare events) decreasing to the right on the horizontal axis and the magnitude of the peak flow represented on the vertical axis on a logarithmic scale.

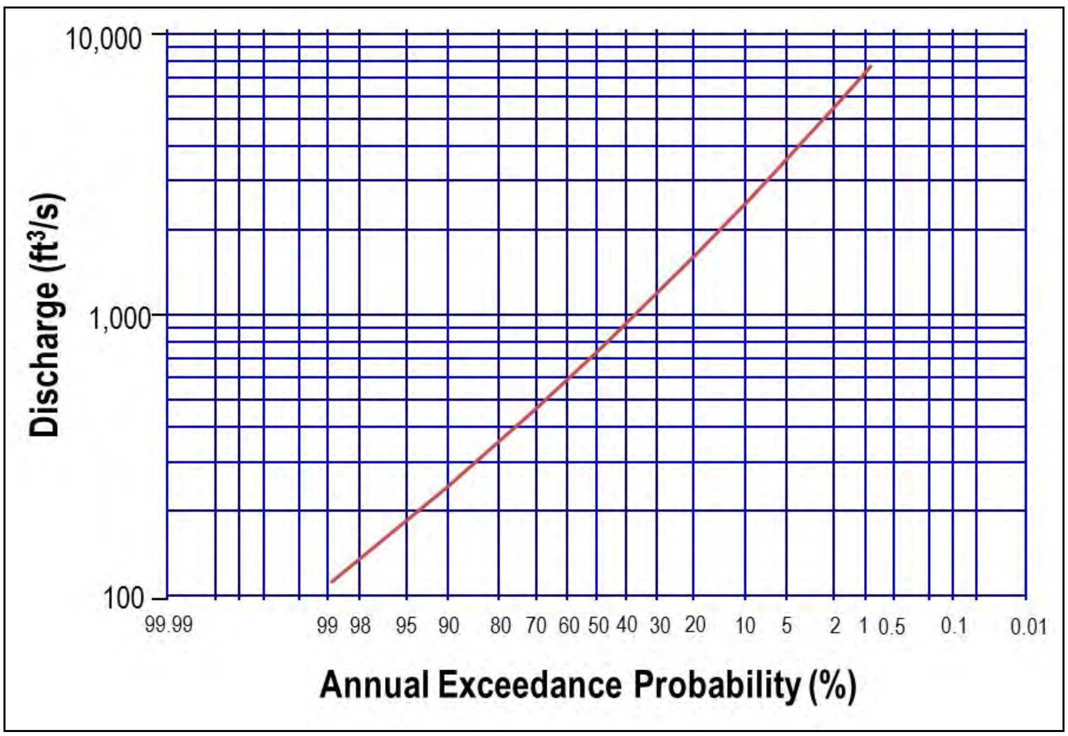


Figure 3.4. Example of a flood frequency curve.

3.2.1. Rainfall/Runoff Models

The broad class of technologies termed rainfall/runoff models comprises three groups: 1) the rational method and its derivatives, 2) the unit hydrograph method, and 3) other tools. Most rainfall/runoff models used in the transportation field, including the rational and unit hydrograph methods, are event-based. That is, the modeler provides a single rainfall event as an input to the model and the output of the model represents the estimated flow for that rainfall for each desired AEP.

An important assumption inherent in rainfall/runoff models is that the runoff AEP (or return period) computed using the model is the same as the rainfall AEP. For example, in using a rainfall/runoff model, the modeler assumes that a 10 percent AEP rainfall produces a 10 percent AEP peak runoff. Working against this assumption is that rainfall events tend to occur in groups. Two identical rainfall events will likely produce different runoff depending on the soil moisture present before the storm. A storm that occurred after a series of storms, resulting in wet soil conditions, might produce a higher runoff than the same storm that occurred on dryer soils.

Extreme floods can result from a single extreme precipitation event, from a sequence of more frequent precipitation events, or by a sequence of relatively frequent precipitation events followed by an extreme precipitation event. If the sequence of events is such that the soil profile is relatively saturated by antecedent rainfall, then a more common rainfall event can produce an extreme runoff event because infiltration capacity is substantially reduced over the average condition.

All rainfall/runoff models rely on estimates of precipitation depth (or intensity) and duration that could represent a historical storm or a design rainfall event. The precipitation depth and duration for a design storm is associated with the desired AEP. Depending on the application (method), the rainfall intensity might be uniform over the storm duration. Other methods require a design hyetograph (rainfall time distribution) reflecting variable rainfall intensity over time.

NOAA Atlas 14 Precipitation Data

NOAA Atlas 14 provides high quality current precipitation estimates for a variety of durations and return periods for most U.S. states and territories. These data are available at NOAA's Precipitation Frequency Data Server (PFDS):

http://www.nws.noaa.gov/oh/hdsc/index.html

Historically, designers took rainfall estimates from atlases such as the U.S. Weather Bureau Technical Paper 40 (Hershfield 1961) and National Weather Service Hydrometeorological Memorandum 35 (NOAA 1977). FHWA recommends the reanalyzed precipitation data of the NOAA Atlas 14 (see inset). In addition, many states and localities have developed or use other sources of precipitation data. Precipitation estimates for the same location, but from different sources may differ because the data cover different periods of record, use different computation techniques, or for other reasons (see inset).

TP40 and NOAA Atlas 14

Care should be taken to select the most appropriate data source. NOAA Atlas 14 is more recent than TP40 and should be used in most cases. The differences vary from place to place. Differences in selected rainfall depths for the Minneapolis/St. Paul area are here:

	10-year	
Duration	TP40	Atlas 14
1-h	2.1	2.1
24-h	4.1	4.2

	100-year	
Duration	TP40	Atlas 14
1-h	3.0	3.6
24-h	6.0	7.5

3.2.1.1. Rational Method

Kuichling (1889) developed the rational method in the late 1800s when engineers observed that urbanized watersheds produced an approximately linear runoff response to precipitation and drainage area. The observations were semi-quantified (Cleveland *et al.* 2011) and resulted in the equation that is identified as the rational method:

$$Q = CiA \tag{3.1}$$

where:

Q = estimated peak discharge, ft^3/s

C = runoff coefficient, dimensionless

i = average rainfall intensity over the time of concentration, in/h

A = watershed drainage area, acres

Designers have used the rational method for a wide range of watershed drainage areas including applications with relatively large watersheds for railroad drainage design (Thompson 2006). However, because peak discharge is not generally related linearly to watershed characteristics such as runoff coefficient and drainage area and meteorological variables such as rainfall intensity, application of the rational method is commonly limited to watersheds with drainage areas of 200 acres or less. (See HDS 2 Section 5.3 for more detail on the rational method (McCuen *et al.* 2002)).

The rational method has the potential for addressing future conditions. Land Use/Land Cover (LULC) changes may be incorporated by changing the runoff coefficient and the average rainfall intensity (through changes to the time of concentration). The method also includes a precipitation intensity parameter that could be used to reflect changes in precipitation.

3.2.1.2. NRCS Graphical Peak Method

The Natural Resources Conservation Service (NRCS) graphical peak method is another approach for estimating design peak discharges. (See HDS 2 Section 5.2 for a detailed description (McCuen *et al*. 2002).) The approach uses the NRCS Curve Number to estimate runoff from design rainfall. The method relies on selection of a runoff curve number from site soils and land use/land cover, then uses the following relation to estimate the peak discharge,

$$q_p = q_u A Q \tag{3.2}$$

where:

q_p = estimated peak discharge, ft^3/s

q_u = unit peak discharge, ft^3/s/mi^2/in

A = watershed drainage area, mi^2

Q = depth of runoff, in

The NRCS Graphical Peak method has the potential for addressing future conditions. Land Use/Land Cover (LULC) changes may be incorporated by changing the curve number and time of concentration. The method also includes a precipitation depth parameter that could be used to reflect changes in precipitation.

3.2.1.3. Unit Hydrographs

The Tennessee Valley Authority first developed the unit hydrograph method for modeling riverine flood hydrographs (Sherman 1932). The conceptual basis of the unit hydrograph method is that a unit depth (volume) of excess rainfall (rainfall less losses) of a specific duration will produce a direct runoff hydrograph (the unit hydrograph) that represents the hydrologic response of the watershed. Given the unit hydrograph for a watershed, the principle of superposition is used construct direct runoff hydrographs from excess rainfall hyetographs. If the direct runoff hydrograph from an actual event is desired, then the hyetograph of rainfall from that event (measured rainfall) is used in the method. If a design hydrograph is desired, then a design (synthetic) rainfall hyetograph is used.

Application of the unit hydrograph method requires three types of data: 1) a unit hydrograph for the watershed, 2) a rainfall hyetograph (actual or design storm), and 3) a method to estimate rainfall losses. Several methods are available for estimating rainfall losses. One method is the Green-Ampt method; the parameters used in the method are readily obtained from published soil surveys. Another common method is the NRCS Curve Number method. Other methods are also available. HDS 2 Section 6.1 provides more details (McCuen *et al*. 2002).

The unit hydrograph method can accommodate adjustments resulting from LULC changes to the watershed by incorporating changes to variables describing impervious area, changes in rainfall loss parameters, and changes to the unit hydrograph attributable to changes in time of concentration.

3.2.1.4. Uncertainty in Rainfall/Runoff Models

Uncertainty estimates are generally not available for rainfall/runoff models. Probability distributions are rarely associated with the input variables and parameters for these models (with the exception of rainfall). Hydrologists and hydrometeorologists develop or use precipitation inputs derived from frequency analysis of historical rainfall data. In these applications, a measure of uncertainty for the rainfall estimate is available, but incorporating this information into design is rare. Unless uncertainty estimates of the input variables and model parameters are available or developed, the designer cannot estimate the uncertainty of the rainfall/runoff model output.

Uncertainty is important because the frequency and magnitude of the flood events that a project will experience over its service life is subject to uncertainty. If designers evaluate only a single event without considering the uncertainty in the estimated design flow then the outcome of an (statistical) error on the design flow and the potential impact on the serviceability of the designed structure remains unknown. In the absence of uncertainty estimates, sensitivity analyses can be used to test the consequences of variations that might occur in rainfall/runoff model variables.

3.2.2. Statistical Runoff Models

Statistical runoff methods are based on statistical analysis of measured discharge data. Although statistical methods can be (and are) applied to precipitation, in general hydrologists and engineers analyze measured stream discharges because frequency distributions of precipitation are completed by others and published. Maximum instantaneous discharges (peak discharges) are obtained from U.S. Geological Survey (USGS) or other streamgaging records and subjected to statistical analysis. The result of the statistical analysis is a set of quantile estimates of peak instantaneous discharge associated with a particular annual exceedance probability (AEP). For example, the discharge associated with the one percent AEP is the upper 0.01 quantile of the fitted probability distribution. Dawdy *et al.* (2012) provide an excellent synopsis of the development of statistical methods. HDS 2, Chapters 4 and 5, discusses statistical methods in the context of the highway environment (McCuen *et al*. 2002).

Engineers and hydrologists generally consider methods that use measured stream discharges superior to rainfall/runoff models because they derive the flood frequency curve directly from streamflow measurements. The parameters used in the probability distributions are derived from observations of streamflow and the resulting flood frequency curve AEPs are closely tied to the underlying sample of peak discharges. If stream data are available, then that data should be used for estimating the flood frequency curve and/or for calibrating a rainfall/runoff hydrologic model.

3.2.2.1. Analysis of Measured Streamflows

If the watershed of interest has a stream gage at or very near the design/analysis site, then the practitioner can derive the flood frequency curve directly from statistical analysis of the annual maximum series of gaged flow data. If a gage is representative of the watershed, but not very near the design site practitioners can use a regionalization method to transpose the flood frequency curve from the stream gage to the design site in some situations.

The most common probability distribution used for flood frequency curve estimates is the Log-Pearson Type III (LPIII). The Water Resources Council Bulletin 17B (IACWD 1982) presents details on the development and application of the LPIII. Implementation of this method involves fitting a Pearson Type III distribution to the logarithms of the annual flood peak series. Bulletin 17B presents the mechanics for development of the skew parameter, as well as methods for handling outliers (odd events) and historical observations. HDS 2 Section 4.3.4 summarizes the Bulletin 17B method (McCuen *et al*. 2002).

The Hydrologic Frequency Analysis Work Group (HFAWG) of the Subcommittee on Hydrology of the Advisory Committee on Water Information has enhanced the Bulletin 17B methods including new statistical techniques for fitting the Pearson Type III distribution. The enhancements include a test for trends in annual peak flows. Such trends in the data might result from land use change, climate change, climate variability (wet and dry periods), or any combination thereof. These changes are implemented in the USGS software analysis program PeakFQ (Veilleux *et al*. 2014).

3.2.2.2. Confidence Limits and Intervals

Peak flow estimates generated from gage flow data also include a measure of uncertainty associated with those estimates called the ***confidence interval***. The confidence interval is defined by a lower and upper ***confidence limit***. (An example of confidence interval is presented in Figure 3.5, which is discussed in detail below.) By comparing the confidence limits with the flood frequency curve the designer has a tool to interpret quantitatively the degree of uncertainty present in the flood frequency curve for any AEP on the curve. HDS 2 Section 4.3.5.2 discusses confidence limits (McCuen *et al*. 2002).

The “fitted frequency” line in Figure 3.5 is an example of a flood frequency curve derived from the annual peak series of flow data from the Big Sandy River at Bruceton, TN (Veilleux *et al*. 2014). The plotted data points represent the measured annual peak discharges from the streamgaging station. The two curves above and below the flood frequency curve are the confidence limit curves and represent the upper and lower confidence limits, respectively.

For the 50 percent AEP (2-year return period) event, the estimate of peak discharge from the flood frequency curve is about 5,000 ft^3/s. The 90 percent confidence interval about that estimate is from about 4,200 to 6,000 ft^3/s, which is a span from about 0.84 to 1.2 times the expected value. The designer interprets the 5,000 ft^3/s as the best estimate of the 50 percent AEP flow, but understands that the true value has a 90 percent probability to be actually between 4,200 and 6,000 ft^3/s. For the 1-percent AEP (100-year) event (about 27,000 ft^3/s), the confidence interval is much greater, from about 19,000 to 45,000 ft^3/s, or about 0.73 to 1.7 times the expected value. (The remaining information on the figure is not pertinent to this topic and may be ignored.)

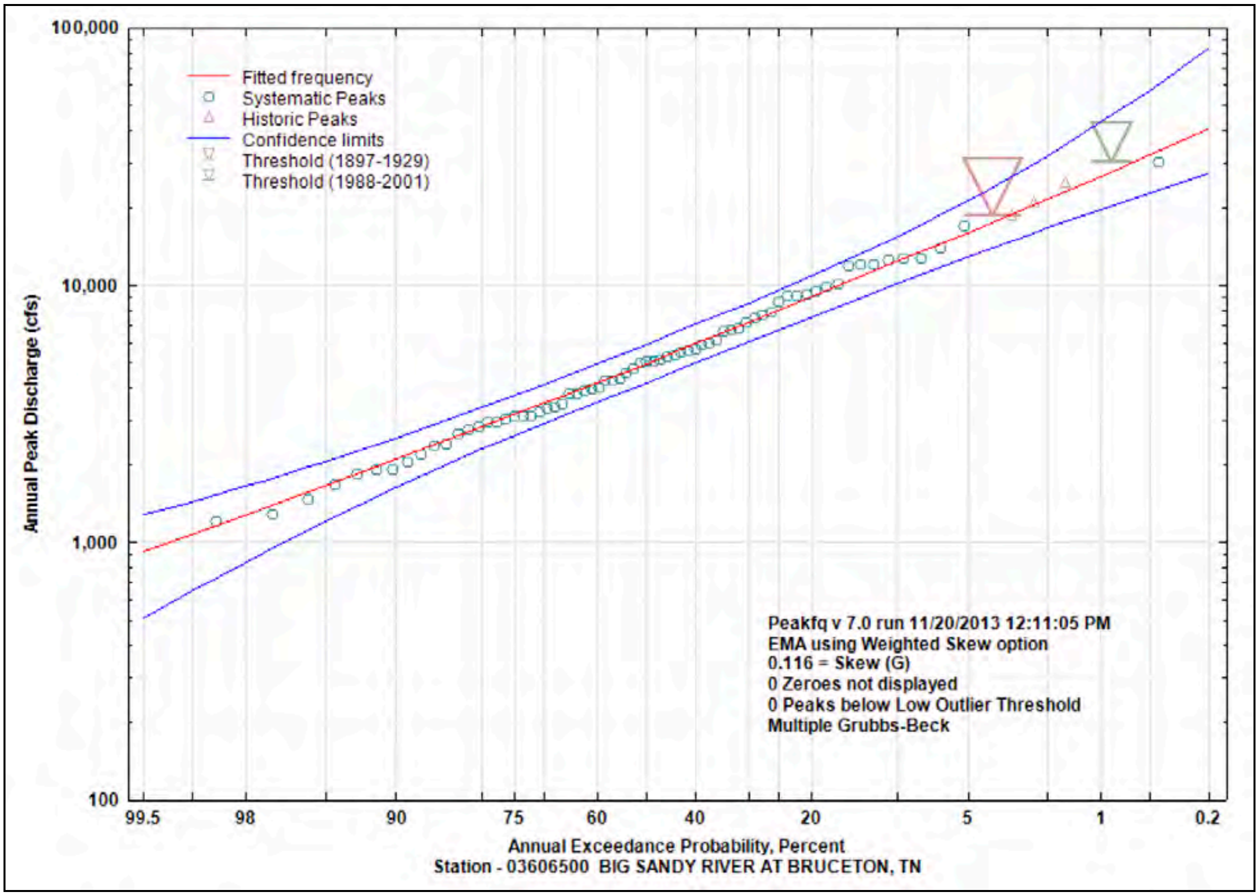


Figure 3.5. Example flood frequency curve with confidence intervals.

The width (size) of the confidence interval about each estimate of the flood frequency curve is dependent on a number of factors, including the probability distribution parameters and length of record. It is most sensitive to length of record with shorter records (fewer observations) resulting in an increased width of the confidence interval (increased uncertainty).

Another way of understanding the information provided by confidence limits is to consider that the flow estimate for a given AEP may actually have a different frequency of occurrence. Revisiting the 1 percent AEP (100-year) estimates for the Big Sandy River (Figure 3.5), the 90 percent confidence limits ranged from 19,000 to 45,000 ft^3/s around a best estimate of 27,000 ft^3/s. If an asset is designed for 27,000 ft^3/s and the true value is closer to 45,000 ft^3/s, then the asset is under-designed and will experience a flood of 27,000 ft^3/s more frequently than anticipated. Conversely, if the asset is designed for 27,000 ft^3/s and the true value is closer to 19,000 ft^3/s, then the asset is over-designed and will experience a flood of 27,000 ft^3/s less frequently than anticipated.

3.2.2.3. Regional Regression Equations

Where gaged data are not available, regional regression equations are an important statistical tool for regionalization of hydrologic data and frequency analysis. Regional regression equations developed by USGS for all states, generally in cooperation with state departments of transportation, are available in reports at:

http://water.usgs.gov/osw/programs/nss/NSSpubs_Rural.html.

USGS personnel and others develop regional regression equations by detailed study of the strength of predictor variables in relation to the estimated flow quantiles on the flood frequency curves for gaged sites. Designers can then apply these relations to ungaged watersheds. Transportation agencies frequently engage the USGS to develop regional regression equations covering their jurisdictional territory.

Predictor (independent) variables generally include some combination of watershed and meteorological characteristics. Examples include the 2-year 24-hour precipitation, mean annual precipitation, watershed drainage area, longitude (or latitude), and length of the main channel of the watershed. The value "predicted" by the regression equation is called the "response" (dependent) variable and is generally the peak discharge.

An example regional regression equation with one predictor variable is (Asquith and Thompson 2008):

$$Q_{100} = 2080A^{0.5094} \tag{3.3}$$

where:

Q_{100} = estimate of the 100-year peak discharge, ft^3/s
A = watershed drainage area, $mi^{2,}$

Development of regional regression equations produces the parameters for the regression equation and estimates of the resulting error (uncertainty) of the peak discharge in the form of a ***standard error***. The standard error represents the expected error using the equation for flow estimates. A greater standard error means that the estimate of peak discharge is more uncertain. For example, the logarithm of the standard error in Equation 3.3 is 0.37. Adding and subtracting this value from the logarithm of the estimated peak discharge provides a range within which the true peak discharge occurs with a 68 percent probability (a 68 percent confidence interval). Each regression equation from each region of the country has its own standard error estimate of uncertainty that typically ranges from 0.10 to greater than 0.37. HDS 2 Section 5.1 has more detail on regression equations and standard error (McCuen *et al*. 2002).

Most regional regression equations apply only to undeveloped or less-developed watersheds. However, some regional regression equations include variables, such as percent imperviousness, that reflect urbanizing or urbanized conditions. In addition, the USGS has developed national regression equations for watersheds affected by urbanization based on a predictor variable called the Basin Development Factor (BDF) (Sauer *et al.* 1983, McCuen *et al*. 2002).

3.3. Extreme Flood Events

FHWA Order 5520 defines an extreme event as the "risks posed by climate change and extreme weather events. The definition does not apply to other uses of the term nor does it include consideration of risks to the transportation system from other natural hazards, accidents, or other human induced disruptions" (FHWA Order 5520 2014). Because the focus of the Order is climatic (climate change and extreme weather), it does not include other hazards, such as seismic, fire, or other sources of risk.

While extreme weather events come in many forms, the focus of this manual is on a subset of those events: ***extreme floods***. The operational definition of extreme for hydrologic designers depends on the magnitude and frequency of the flood event, the nature of the infrastructure exposed, and the potential for losses. This balance also depends on the national tolerance for potentially severe consequences in the future and on the ability for capital expenditures and management strategies today. Therefore, the definition of an extreme flood event is ultimately qualitative and may change over time.

The appropriate ***design flood*** depends on the nature of the infrastructure and the risks of damages and other losses. Customarily, practice defines the design flood solely by its peak flow rate, but the total flood volume and duration may also be important in evaluating risks. While design procedures specify the design flood (or flow) primarily on the frequency of its occurrence, practice sets the appropriate frequency by considering acceptable consequences.

For example, if the potential consequence of a flood event is loss of service to transportation infrastructure for substantial periods (hours, days, or weeks) and the infrastructure provides access to emergency facilities or is a major conveyance of emergency responders, then the engineer or analyst might consider that flood event “extreme” and measures to mitigate loss of service are appropriate. If the potential for damage to adjacent properties is substantial, or if critical services (electrical, communications, or medical, for example) might be substantially affected, then the engineer or analyst may also consider the flood event under consideration to be extreme. Conversely, if the consequences of a flood were not significant, then the flood event would generally not be considered extreme.

The focus of this manual is on peak flood events associated with an AEP of 10 percent or less (10-year return period or more). While not an extreme event, this threshold allows a focus in this manual on the sources of data, hydrologic techniques, and adaptation strategies appropriate to these larger floods.

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Chapter 4. Nonstationarity and Climate Change

Designers responsible for estimating flow rates as a basis for modifying existing or designing new transportation assets at least implicitly consider three time horizons: 1) the past, 2) the present, and 3) the future. Practice characterizes the past by measurements of rainfall, flow, and watershed characteristics. Practice frames the present by current design standards and tolerance for risk. Practice views the future in the context of the useful life of transportation assets. ***Stationarity*** holds that the data from the past is representative of the future and can be used for analyzing that future. ***Nonstationarity*** means that patterns or trends of the past may not be valid in the future.

As described in Chapter 3, hydrologic data and methods result in uncertainty regarding flow estimates. Nonstationarity represents another source of uncertainty and may place limits on the use of historical information to estimate future flooding. A critical question is whether nonstationarity significantly expands uncertainty or represents only a small increment. The answer to this question may be highly variable and based on the time horizon and location in the country. Some investigators such as Cohn and Lins (2005) have suggested that the natural climatic variation renders insignificant any human-induced changes observed over the past century.

This manual addresses the two primary sources of nonstationarity: land use/land cover (LULC) and climate change. Depending on the life expectancy of the project, expected changes may range from little or no change from the existing (or historical) condition to major changes in LULC or climate. This chapter describes nonstationarity, tools to identify trends, and strategies for adapting to nonstationarity.

4.1. Defining Nonstationarity

An inherent assumption in most hydrologic design tools is that the variables and parameters used in the models do not change over time. Stationarity means exactly that — the system is not subject to temporal change. Nonstationarity might result from changes in watershed land use/land cover and changes in climate. Additional sources of nonstationarity include dam construction (and removal), other watershed detention facilities, stream diversion (for agricultural or municipal use), and other changes within the watershed that influence flooding. Nonstationarity could be realized as an abrupt change, periodic variability, or a trend.

An ***abrupt change*** is one that occurs abruptly in the time series. Such cases are generally associated with placement or removal of dams on river systems. The construction or removal of a dam dramatically affects the watershed response immediately downstream from the dam. The effect is reduced with increasing distance from the dam (and increasing watershed drainage area).

A ***periodic variability*** occurs when cycles of wet and dry periods occur in the time series. These cycles are usually multi-year in length. For example, Figure 4.1 exhibits groups of flood events apparent in the time series graph that represent a periodic variability in the annual series of floods on the river. The source of this behavior in the Pedernales River time series is undetermined, though it could be associated with the El Nino/Southern Oscillation (ENSO) behavior as that is a driver for Texas climate. Observations beyond the range of periodic variability still may occur. For example, a very high discharge of 440,000 ft^3/s is observed in 1953 that is clearly outside of the range of periodic variability.

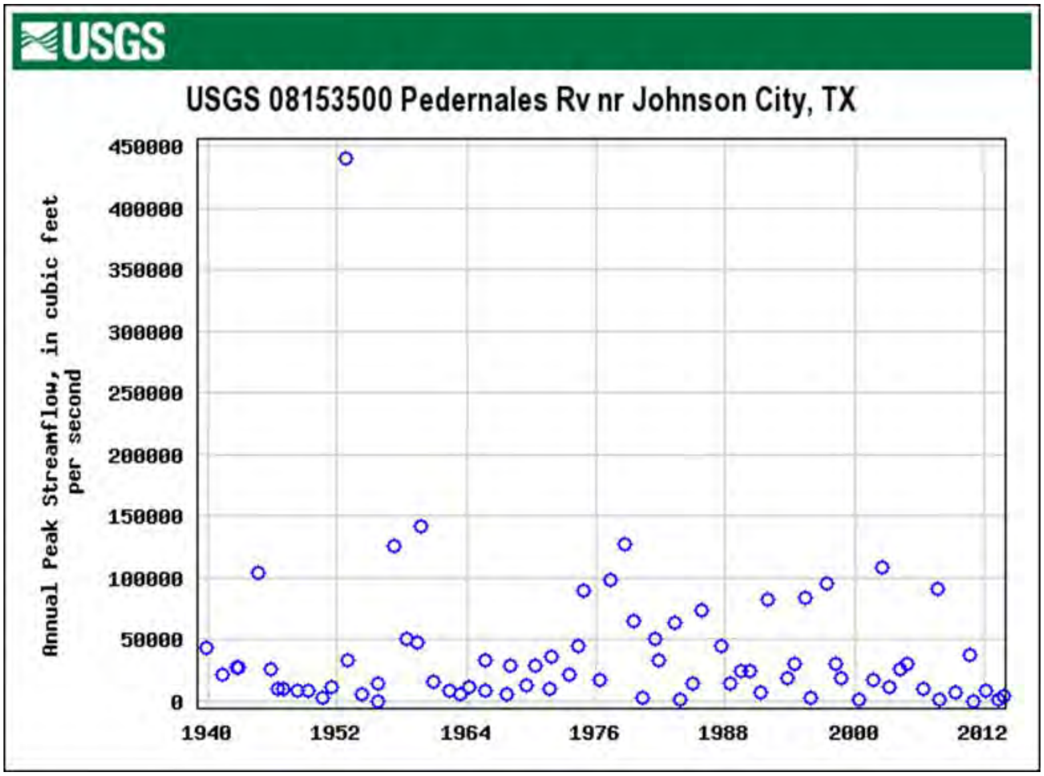

Figure 4.1. Annual peak streamflow series, Pedernales River, Texas.

The upper panel of Figure 4.2 presents an example of a ***trend*** (Konrad 2003). In the upper panel, an increase in annual peak discharge as a function of time (a trend) for Mercer Creek is readily visible. The most likely source for the trend is watershed development (increased impervious area and decreased watershed response time). In the lower panel, there appears to be no trend in the annual peak series for Newaukum Creek over the same period of record. Both creeks are in the same hydrologic/climatic region.

4.1.1. Land Use/Land Cover Changes

One source of nonstationarity is the development of the watershed. Barros and others analyzed records from about 10,000 stream gaging stations in the southeast portion of the United States (Barros *et al.* 2014). These researchers reported evidence of alignment of nonstationarity at the regional scale with land use/land cover changes associated with urbanization during the preceding 100 years. The researchers primarily detected changes in less frequent events (25-year and 100-year return periods).

Land use changes can mean any physical change to the watershed, including residential, commercial, and agricultural development. Some jurisdictions require use of “built-out” conditions for assessment of, and impacts to, the flood frequency curve. The use of built-out or ultimate development conditions for hydrologic analysis of watersheds is one strategy for managing watersheds and floodplains. However, this approach is not universally accepted because projected development may not occur or the community may implement runoff detention criteria to mitigate the peak flow effects of that development.

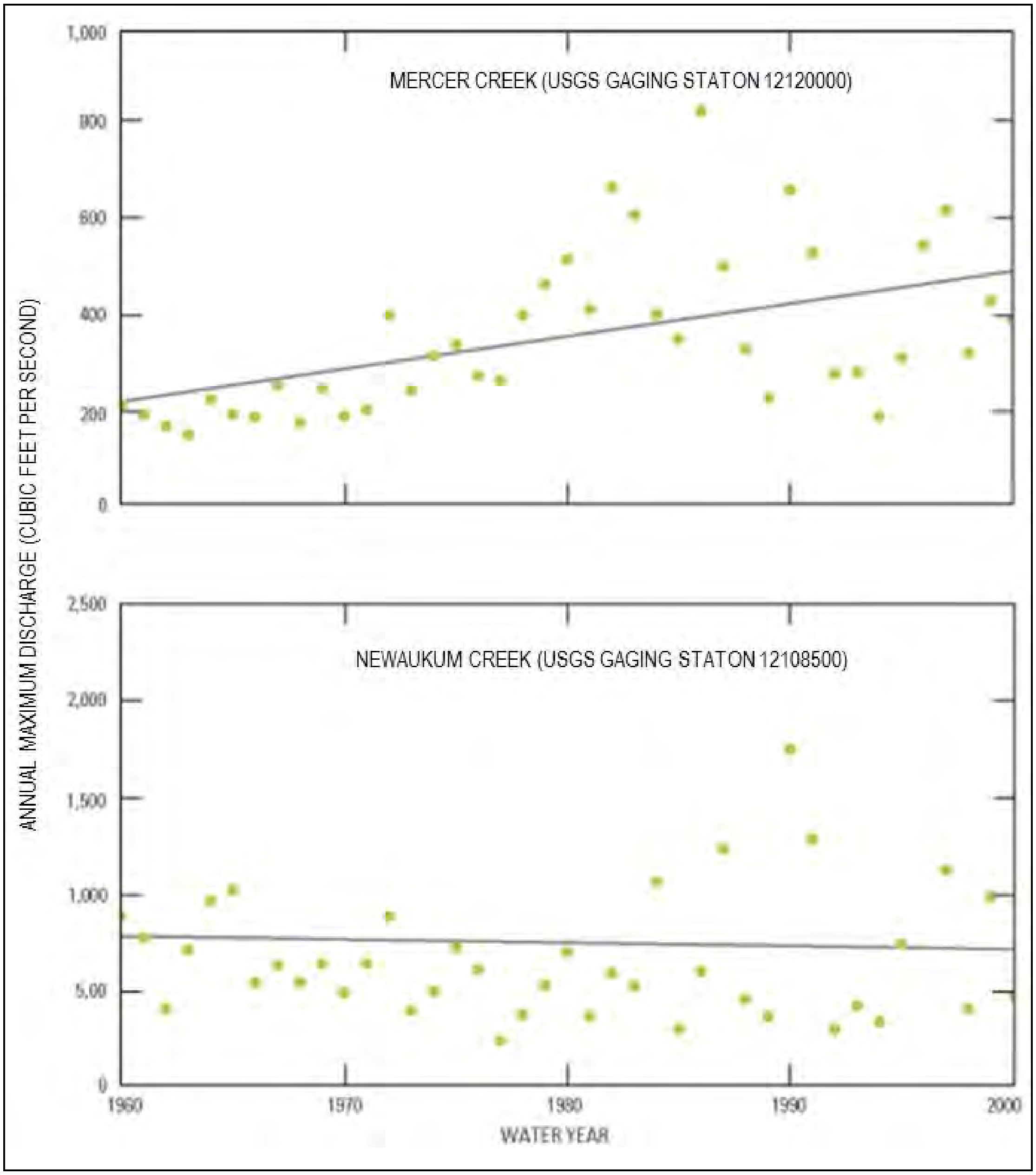

Figure 4.2. Annual maximum discharge from Mercer Creek and Newaukum Creek, Washington.

4.1.2. Climate Change

Climate change may also contribute to nonstationarity. Climate can be characterized by many different variables including temperature and precipitation with different metrics such as mean values versus extreme values. Therefore, the term "climate change" can have different implications for climate scientists and the engineering community. The definition of climate change used in this manual includes the following concepts:

- a significant and lasting shift in the statistical distribution of weather patterns around the average conditions,

- any significant shift in the measures of climate lasting for an extended period of time, and
- a non-random shift in climate that is measured over several decades or longer. The change may result from natural or human-induced causes.

The definition refers to the statistical distribution of weather patterns and measures of climate. Climate change represents long-term changes in precipitation and temperature patterns rather than the normal climate cycles of drought and wet periods documented in the historical record. There have been significant multi-decadal droughts, ice ages, and warming periods throughout the past millennia of our planet's geologic history.

With respect to temperature data there is significant evidence that the planet has warmed over the past century. In general, a warmer atmosphere can hold more water and this could lead to larger storms with increased intensities. A warmer climate may mean more annual precipitation falling as rain instead of snow; and when snow does occur, it will melt more quickly leaving less water to create floods in the spring when temperatures rise and rain on snow events occur. Alternatively, a warmer climate can lead to drier soil conditions, increasing the amount of infiltration from a given storm and hence less runoff. However, very high temperatures could "bake" the soil resulting in it being less able to infiltrate rainfall, leading to increased runoff. Climate change, then, could either increase or decrease flood risk depending upon local conditions and the hydrology of local floods.

4.2. Precipitation and Flooding in the Historical Record

It is important to understand trends in the past climate as a basis for anticipating potential future change. Many papers in the literature describe the trends in the historical precipitation and flood data in the United States. This section summarizes pertinent papers characterizing trends in precipitation and flood frequency in the historical record.

4.2.1. Precipitation

With respect to climate change, it is important to determine the climatic variables that are changing and the corresponding effect, if any, on the design and maintenance of transportation assets such as bridges and culverts. To accomplish this goal successfully, climate scientists and engineers should share a common language. However, climate scientists and engineers often use inconsistent terminology and reference different climatic variables when characterizing the trends and potential effects of climate change.

Climate scientists generally analyze daily (calendar day) precipitation and characterize magnitude and frequency with qualitative terms such as ***heavy, very heavy,*** or ***extreme***. For example, Groisman *et al*. (2005) characterized precipitation as:

- ***heavy*** when the magnitude falls into the upper 10 percent or 5 percent of all daily precipitation events,
- ***very heavy*** when the magnitude falls into the upper 1 percent or 0.3 percent of all daily precipitation events, and
- ***extreme*** when the magnitude falls into the upper 0.1 percent of all daily precipitation events.

By contrast, the engineering community has typically analyzed annual maximum series or partial duration series of 24-hour (not calendar day) or other duration precipitation data rather than cumulative distribution data. The engineering community defines frequency of these data in terms of return periods that range from 0.50 to 0.01 annual exceedance probability (2- to 100-year return period) or even 0.002 annual exceedance probability (500-year return period) in designing hydraulic assets and evaluating the impacts of scour. Groisman *et al.* (2005) equate very heavy precipitation to a return period of approximately one daily event in 3 to 5 years for annual maximum daily precipitation. Hence, the frequency and intensity of precipitation emphasized in much of the climate literature is at the lower end (smaller magnitude, more frequent) of the range of events typically used by the engineering community.

Identification of trends in precipitation in the historical record can depend on the type of precipitation statistic considered. Groisman *et al*. (2005) concluded that ***very heavy*** precipitation has increased during the period of instrumental observations over most of the contiguous U.S. and that the evidence is growing that historical trends in “very heavy precipitation” are linked to climate change. However, Groisman *et al*. noted it is difficult to relate estimates of changes in very heavy precipitation with changes in flooding.

Karl and Knight (1998) observed that the proportion of total precipitation derived from daily events exceeding 2 inches – their definition of extreme precipitation - increased relative to lower rainfall rates. (Note that the definition of Karl and Knight differs from that of Groisman *et al*.)

However, events in the 2 to 3 in/day range generally do not produce high flows or floods except under rare circumstances when antecedent conditions have been anomalously wet. A review of annual flood information compiled by USGS indicated that precipitation rates typically associated with significant flooding are approximately 3 in/h, 5-16 in/day, and 17 to 20 inches in three days (Perry *et al*. 2000). Here again, the climatologists’ definition of extreme precipitation is less than what an engineer would consider extreme because the storms are too small to cause significant peak discharges.

Peterson *et al*. (2013) acknowledge that days with heavy precipitation have been increasing significantly across the eastern United States, but interestingly, observe that this trend is not strongly related to changes in river flooding. Possible reasons for this mismatch include that flooding in most river basins larger than 390 mi^2 generally respond to longer-duration precipitation events and because some of the changes in heavy precipitation occur during seasons that generally do not produce floods. For example, an area such as the northern Great Plains, where peak flooding most often occurs during spring snowmelt, tends to experience the heaviest daily rainfall events during summer convective storms when antecedent moisture conditions are dry. Additionally, some of the greatest floods in the last few decades, such as the great upper Mississippi River flood of 1993, have been in response to seasonal and longer duration extreme events.

Bonnin *et al*. (2011) highlight that the lack of common usage of the term “extreme” between climate scientists and civil engineers is a source of frequent miscommunication that obscures the discussion on the potential impact of climate change on civil infrastructure by the climate community. Bonnin *et al*. analyzed the trend in the frequency of exceedances of several recurrence interval precipitation events (ranging from 1 to 100 years) for the 6-hour, 24-hour, and multiple day rainfall durations for the Semiarid Southwest (Volume 1 of NOAA Atlas 14) and the Ohio River Basin (Volume 2 of NOAA Atlas 14). They used data from 1948 to 2007 for the 6-hour duration and a longer record from 1908 to 2007 for the 24-hour and multiple day durations. Using the Mann-Kendall test statistic to determine if the trends in the frequency of exceedances were statistically significant, Bonnin *et al*. concluded:

- For the Semiarid Southwest region, for durations of one or more days almost all are downward trends, but the trends are statistically significant for only the 1-day duration. At the 6-hour duration, all trends are upward, but not statistically significant.
- For the Ohio River Basin and surrounding states, the trends are upward for most durations and recurrence intervals. At durations of 1- to 20-days, almost all trends are statistically significant, whereas for the 6-hour and 45-day durations most trends are not statistically significant.

> ***Statistical Significance***
>
> *Statistical significance is a phrase that summarizes the result of a mathematical test to determine the likely validity of a hypothesis based on a specified confidence level. For example, consider a test conducted to determine if there is a trend in a time series of annual rainfall maximum depths. The trend is considered statistically significant if the result of the test indicates there is a high probability that the trend exists.*

The magnitude of the trends was small for all except the more frequent events (2- to 5-year) and small with respect to the uncertainty associated with the precipitation estimates. Overall, Bonnin *et al*. concluded that the trend in the western United States is for decreasing precipitation with time whereas in the eastern United States the precipitation is generally increasing with time.

Planners and designers assessing the historical record for precipitation trends should be careful to define the season, magnitude, duration, and frequency of the precipitation statistic of interest to understand the risks to plans and projects revealed by the historic data. As discussed, less extreme precipitation data may exhibit trends, but may not result in changes in the types of floods of interest to engineers.

4.2.2. Flood Magnitude and Frequency

To investigate how national flood records may have varied historically, several investigators have evaluated the existence of trends in flow data. Lins and Slack (2005) investigated seasonal and regional streamflow characteristics in the United States using daily mean discharges for 435 gaging stations from the Hydro Climatic Data Network (HCDN) with records for the 60-year period 1940 to 1999. Lins and Slack performed trend tests on the percentiles of the daily mean discharges. The range of streamflow characteristics was from the annual minimum daily (calendar day) discharge through several percentiles (10^{th} to the 90^{th}) to the annual maximum daily (calendar day) discharge. Lins and Slack reported significant upward and downward trends for 19 of the 21 WRC regions.

A summary of the number of stations with statistically significant trends (at the 5-percent level of significance) for the 435 stations follows:

> ***The Hydro Climatic Data Network (HCDN)***
>
> *The U.S. Geological Survey (USGS) Hydro-Climatic Data Network (HCDN) is a series of stations that have not experienced significant flow diversion or augmentation, regulation by dams or reservoirs, or land-cover changes such as urbanization, which makes them extremely valuable for understanding watershed behavior. The drainage areas for the HCDN stations range from less than 1 square mile to over 10,000 square miles, but more than 75 percent of the stations have drainage areas between 193 and 1,930 square miles.*

- Annual minimum daily discharge: 175 stations with an upward trend, 33 stations with a downward trend.
- Median or 50^{th} percentile discharge: 187 stations with an upward trend, 2 stations with a downward trend.
- 90^{th} percentile of daily discharge (90 percent of daily discharges less than this value): 65 stations with an upward trend, 1 station with a downward trend.
- Annual maximum daily discharge: 43 stations with an upward trend, 15 stations with a downward trend.

Within each region, more stations experienced trends in the low to moderate percentiles of flow than in the upper percentiles, with the fewest trends occurring in the annual maximum data. Forty percent of the stations had an upward trend in the median streamflow. The preponderance of upward trends across the lower half of the discharge distribution is reflective of the observed increase in warm-season (summer and autumn) precipitation reported by Karl and Knight (1998). The lower flows tend to occur in the summer and autumn in most areas of the United States.

Lins and Slack (2005) also investigated if there was a shift in the month of the annual minimum and maximum daily discharges. None of the regions exhibited such a shift in timing based on using monthly mean values. However, in northern regions where snowmelt is a major part of the hydrologic process, there is evidence of earlier springtime runoff because of more rainfall and earlier snowmelt. Dettinger and Cayan (1995) and Stewart *et al*. (2004) reported a shift in timing of one to three weeks earlier for the springtime snowmelt in the western United States. Hodgkins *et al*. (2003) studied changes in the timing of the center of volume of springtime runoff in New England and found a shift up to two weeks earlier, primarily during the last 30 years. These studies used mean daily discharges to evaluate the shift in timing of the runoff.

Design flows for bridges and culverts are based on less frequent (higher return period) flows based on annual instantaneous peak discharges. Hirsch (2011) analyzed annual instantaneous peak discharges for 200 USGS stream gaging stations with 85 to 127 years of record that had no significant upstream regulation or urbanization. Of the 200 stations analyzed, 54 stations had statistically significant trends (19 downward and 35 upward) at the 5-percent level of significance. Hirsch divided the country into four quadrants and found that downward trends are most prevalent in the Southwest and Northwest with many statistically significant downward trends in annual peak discharges in the Southwest as shown in Figure 4.3. In the Northeast and Southeast, upward trends are more prevalent with more statistically significant upward trends in the Northeast. These trends for annual peak discharges are consistent with precipitation trends observed by Bonnin *et al*. (2011).

Villarini *et al*. (2011) analyzed annual instantaneous peak discharges for 196 USGS stream gaging stations with at least 75 years of record in the Midwest US (North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, and Illinois). Villarini *et al*. noted that many of the basins in this area have undergone changes in land use and land cover, agricultural practices, urbanization and construction of dams. Therefore, rather than looking for “pristine” river basins, Villarini *et al*. considered that all river basins have experienced some human alteration. The results of these analyses should reflect the regional impact of human activities on the flood peak distribution. Performing both change-point (abrupt changes) and trend analyses for the 196 stations. Some conclusions from this analysis are:

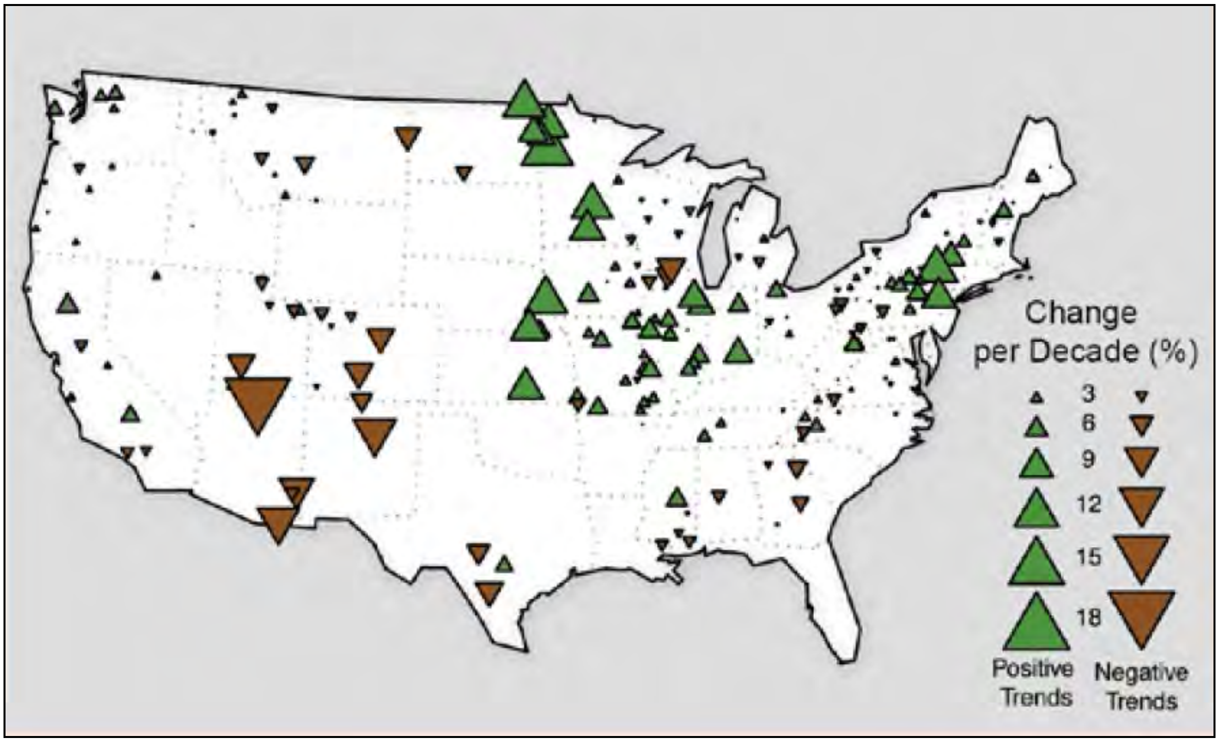

Figure 4.3. Trends in flood magnitude (from Hirsch 2011 and Petersen *et al*. 2013).

- Only a limited number of stations presented a statistically significant trend. There is little indication that anthropogenic land use or climate change has significantly affected the flood frequency distribution for the Midwest US in the twentieth century.
- In the vast majority of the nonstationary cases, the nonstationarity is associated with abrupt changes (change-points) with respect to mean and variance rather than monotonic trends. These nonstationarities are often associated with anthropogenic effects, such as changes in land use/land cover, changes in agricultural practices, and construction of dams and reservoirs. However, some of the observed changes could result from abrupt changes in the rainfall regime in the area.

Lins and Cohn (2011) analyzed annual instantaneous peak discharges for 1,491 stations for the 60-year period 1948 to 2007 from the HCDN. Figure 4.4 shows the increasing trends with upward pointing triangles and decreasing trends with downward pointing triangles. Of these, only approximately six percent (signified by open triangles in the figure) are significant at the 5-percent level based on the Adjusted Likelihood Ratio Test (ALRT). (Of these, 58 stations exhibited downward trends and 38 stations exhibited upward trends.)

As shown in Figure 4.4, there are about an equal number of statistically significant increasing and decreasing trends in the eastern half of the country. For the western half of the country, there are more downward trends than upward trends.

4.3. Detecting and Adjusting for Nonstationarity in the Historical Record

As discussed previously there are two primary sources of nonstationarity in flood data: land use/watershed change and climate change. This section describes techniques for detecting and adjusting for nonstationarity to preserve the utility of measured data for generating design flows.

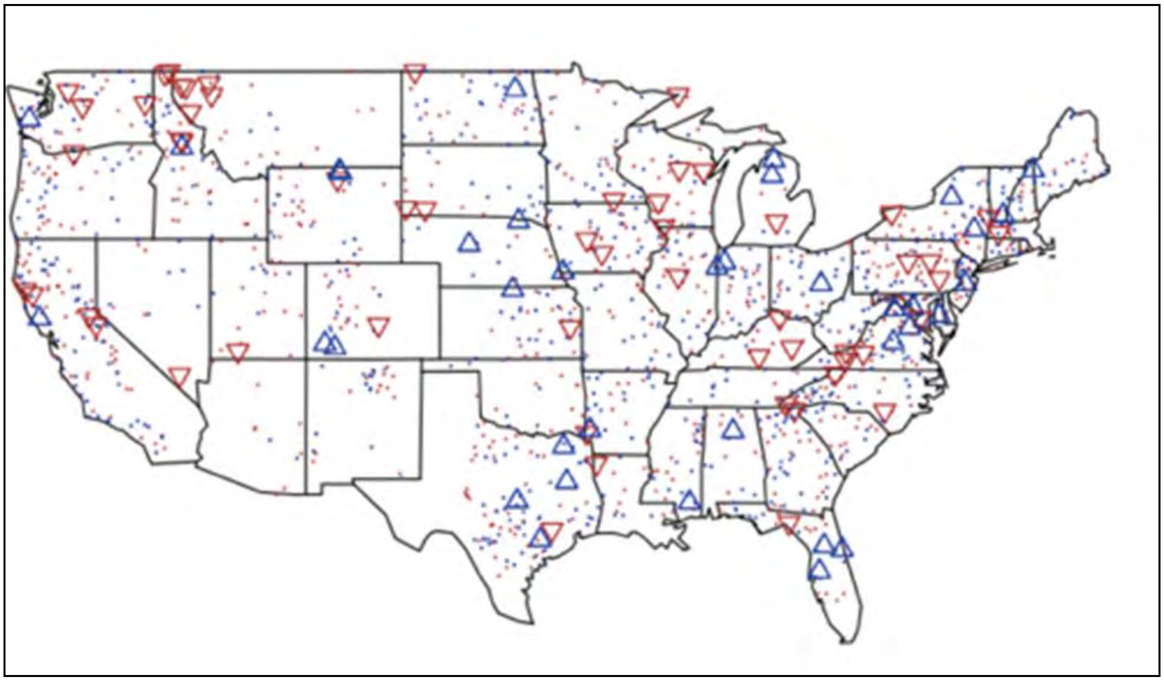

Figure 4.4. Trends in annual instantaneous peak streamflow (from Lins and Cohn, 2011).

4.3.1. Detecting Nonstationarity

Understanding and detecting nonstationarity (trends) rigorously requires the broadest possible perspective on the data. Hirsch (2011) recommends that when determining trends in flood data one should consider all available data including the use of paleoflood and historical information to understand the variability that exists at a site. As illustrated in Figure 4.5 from Hirsch (2011) for the Red River of the North at Grand Forks, North Dakota, the increase in annual peak discharges appears much more dramatic assuming data are available from 1925 to 2009 (left panel) rather than considering the full period of record 1882 to 2009 (right panel).

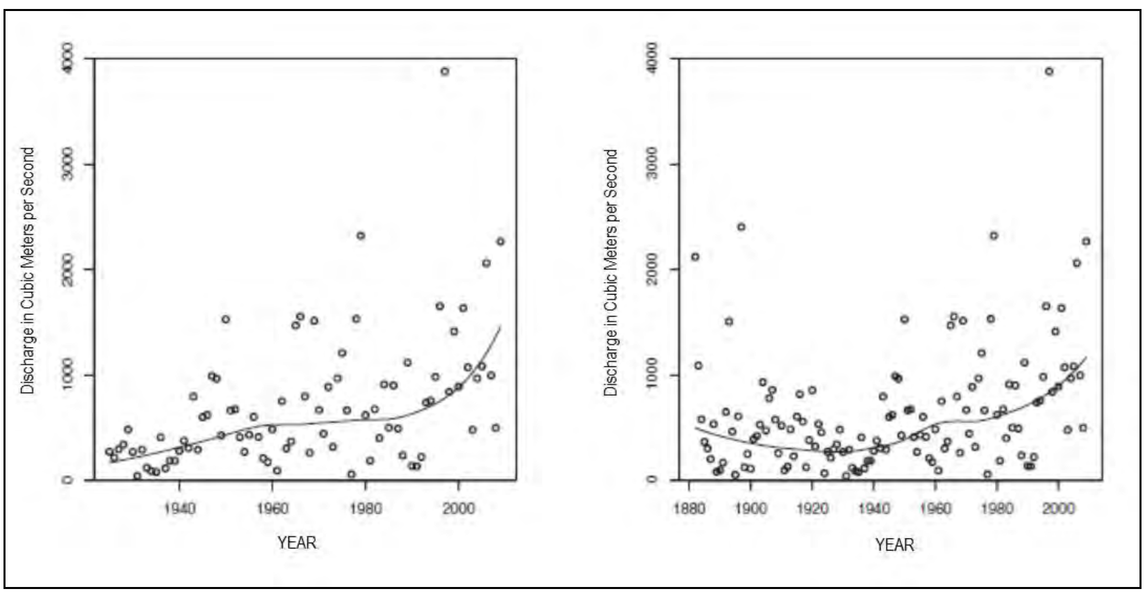

Figure 4.5. Annual peak discharges for the Red River of the North at Grand Forks, ND.

Examining only the most current records or some other subset of data without examination of the full record may lead to erroneous conclusions regarding the effects of land use or climate changes. Examination of the full record may also lead to the conclusion that only parts of the record are representative of the data for design purposes.

Nonstationarity may be characterized by gradual trends over time or abrupt changes in time. The following sections describe common tools for identifying nonstationarity in historical data.

4.3.1.1. Gradual Trends

The most widely used statistical test for detecting nonstationarity or trends in a time series is the Mann-Kendall test (Helsel and Hirsch 1992, McCuen 2003). This test uses Kendall's tau as the test statistic to measure the strength of the relation between annual peak discharges and time (year). The Mann-Kendall test is nonparametric and does not require that the data conform to any specific statistical distribution. The statistic is calculated using the ranks of the observed peak discharges, not the actual data values. The ranks of all pairwise data points are compared to determine if the data series is monotonically increasing or decreasing. Positive values of tau indicate the annual peak discharges are increasing with time and negative values of tau indicate the annual peak discharges are decreasing with time. The Mann-Kendall test is available in several statistical packages and is now included in Version 7.1 of the USGS PeakFQ program (http://water.usgs.gov/software/PeakFQ/).

> ***Northeast Branch Anacostia River***
>
> *The Northeast Branch Anacostia River at Riverdale, Maryland, is a watershed located just east of Washington, DC. The increase in annual peak discharges is primarily related to the increase in urbanization over the period where it was essentially rural in the early 1960s transitioning to 27.4 percent impervious by 2002. In addition, the watershed has been affected by climatic variability. In this region, the 1970s were characterized by several major floods and the last decade or so has been a period of major flooding.*

For example, the annual peak discharges in Figure 4.6 clearly appear to be increasing with time. The Mann-Kendall test provides a tool to quantify the statistical significance of the trend. The output from Version 7.1 of the USGS PeakFQ program is given below for the Northeast Branch Anacostia River at Riverdale, Maryland (01649500) for the full period of record (76 years) as shown in Figure 4.7. The Kendall's tau value is 0.492. Because it is positive, the trend is upward. The p-value provides the measure of statistical significance to the trend. If it is less than 0.05 then a trend exists at the 5-percent significance level. Since the p-value is essentially zero the hypothesis that a trend exists is confidently accepted. The median trend slope is 62.683 ft^3/s/year.

4.3.1.2. Abrupt Changes

The Mann-Kendall test is for detecting a gradual trend in annual peak discharges. In some flow records, there may be an abrupt shift or change in the time series rather than a gradual trend. For example, there may be distinct periods exhibiting different flood characteristics before and after construction of flood control structures. The Pettitt test is a test for abrupt changes and is a nonparametric (rank-based) test that allows detection of changes in the mean (median) when the change point time is unknown (Pettitt 1979, Villarini *et al.* 2009). The Pettitt test identifies the year in which the maximum difference in ranks occurs across the full period of record. The construction of a flood detention structure or major channelization in a watershed is usually well documented and known to the analyst. However, the Pettitt test is useful for detecting episodic change if the analyst is unaware of the watershed history.

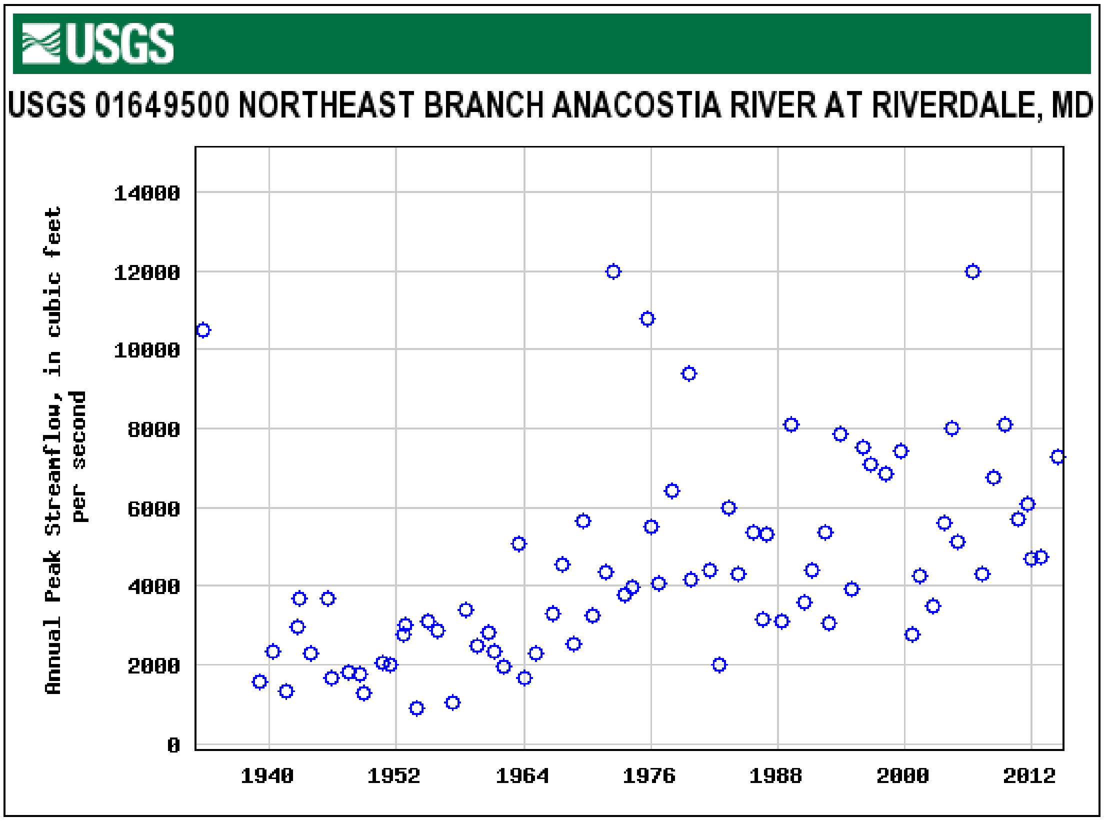

Figure 4.6. Annual peak discharges for the Northeast Branch Anacostia River at Riverdale, MD.

	TAU	P-VALUE	MEDIAN SLOPE	No. of PEAKS
SYSTEMATIC RECORD	0.492	0.000	62.683	76

Figure 4.7. PeakFQ output for the Northeast Branch Anacostia River at Riverdale, MD.

Figure 4.8 provides an example application of the Pettitt test for the Blackwater River near Webster, New Hampshire (White 2015). In 1941, a dam was built for flood control purposes just upstream of the gaging station (01087000) and had a significant impact on the annual peak discharges. The Pettitt test identified a statistically significant abrupt change in the mean of the annual peak discharges in 1942. (The figure erroneously states 1992.)

The U.S. Army Corps of Engineers has prepared a Nonstationarity Detection Tool that facilitates identification of nonstationarities in annual peak flow series data from USGS gaging stations. The Tool includes the Pettitt test among several techniques (Friedman *et al.* 2016).

4.3.2. Adjusting for Nonstationarity

Identifying nonstationarity is the first step to preserving historical data for design purposes. The next step is, where possible, to identify the cause of the nonstationary behavior and adjust the data to account for the identified cause. The following sections discuss data adjustment strategies.

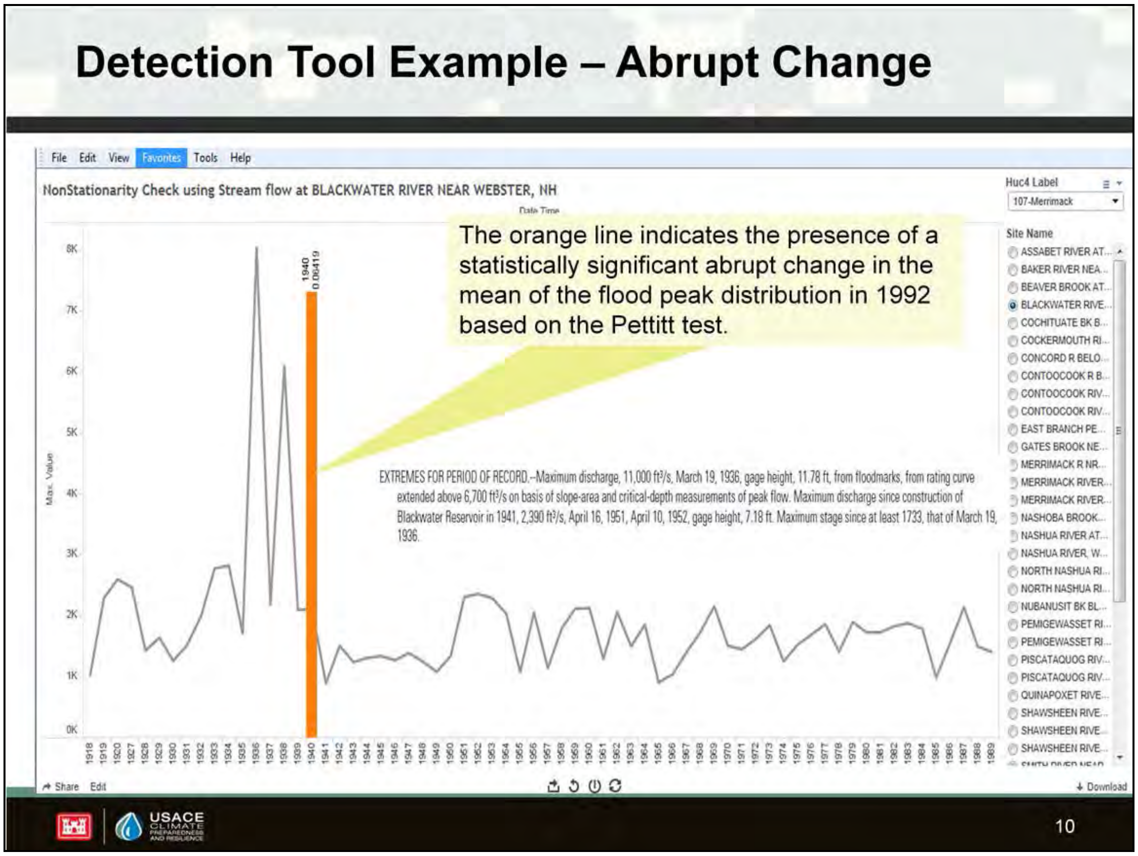

Figure 4.8. Example of the Pettitt test applied for the Blackwater River.

4.3.2.1. Adjustment for Urbanization

For watersheds like Northeast Branch Anacostia River (Figure 4.6) affected by urbanization, McCuen (1989) developed an approach for adjusting historical flood data to current land use conditions. In order to apply this ***index adjustment*** procedure, the designer must estimate the impervious area in the watershed for each year of the record. Using published reports and previous studies, McCuen developed a relation between the peak adjustment factor and exceedance probability and percent imperviousness. HDS 2 Section 4.4 provides a detailed description and example application of this method (McCuen *et al*. 2002).

McCuen described the potential to apply the index adjustment method to other variables that cause nonstationarity in an annual peak flow record. To do so, the driving variable and its direct influence on runoff should be quantified over the period of record.

4.3.2.2. Homogeneous Subperiod of Record

Another approach for preserving data in a nonstationary series is to identify a significant subset of the period of record that is homogeneous and use only that subset for design. The retained data should still represent a long period of record so that it includes natural climatic variations. Preferably, it should be the later part of the full record. This approach may be appropriate when it is not possible to adjust the data to a common reference as described in the previous section.

If urbanization causes the nonstationarity in the full record, then the change in impervious area can be used to define a homogeneous period. Sauer *et al.* (1983) defined “relatively constant urbanization” as a change in development of less than 50 percent during the period of record.

For example, if a basin is 20 percent impervious at the beginning of the record, then it should not be more than 30 percent impervious at the end of the record to be considered homogeneous.

For example, the Northeast Branch Anacostia River watershed discussed previously was 18.9 percent impervious in 1985 and 27.4 percent impervious in 2002 (close to ultimate development). Using the criteria of Sauer *et al*. (1983), the period of 1985 to 2014 is a relatively homogeneous period with respect to land use change. The Mann-Kendall trend test on this period (1985 to 2014) reveals no statistically significant trend for the period. Therefore, the period from 1985 to 2014 is a homogeneous period of record for the Northeast Branch Anacostia River and may be used for flood frequency analysis.

Section 4.3.2.1 and this section describe two techniques for addressing nonstationarities caused by urbanization in a watershed. In the case of the Northeast Branch Anacostia River, both methods are feasible. The designer should evaluate both methods and choose whether a longer record (1938 – 2014) using the index adjustment method or a shorter unadjusted homogeneous period of record (1985 – 2014) better serves the project objectives.

4.3.2.3. Frequency Analysis with a Time Varying Mean

A third approach for adjusting nonstationary data to estimate design flows is through statistical adjustment of the mean. Salas and Obeysekera (2014) describe an approach using the Generalized Extreme Value (GEV) distribution where the mean and standard deviation vary with time. Vogel *et al*. (2011) and Read and Vogel (2015) describe a nonstationary flood model using the 2-parameter lognormal distribution. Read and Vogel (2015) show that the coefficient of variation (standard deviation divided by the mean) is relatively constant for the lognormal distribution so that one needs just a single nonstationary model of the mean to estimate the change in both the mean and standard deviation.

Bulletin 17B recommends fitting the Pearson Type III distribution to the logarithms of annual peak discharges (Interagency Advisory Committee on Water Data 1982). This method requires estimating the mean, standard deviation, and skew of the logarithmic data. The method suggested by Vogel et al. (2011) and Read and Vogel (2015) for the 2-parameter lognormal distribution is extended here to adjust the mean of the Pearson Type III distribution.

Consider a rural 5 square mile watershed in southern Delaware, Stockley Branch at Stockley (station 01484500) as an example. Figure 4.9 summarizes the 62-year record of annual peak flows (1943-2004) established before USGS discontinued the station in 2004. Increased precipitation near the end of the record, most likely attributable to natural climatic variability, caused the upward trend in the annual peak discharges. There are no significant land use changes in the watershed. Using the Bulletin 17B procedure described in Chapter 3 without adjusting for the nonstationarity results in the flow estimates for the 50-, 10-, and 1-percent AEP shown in Table 4.1.

If one analyzes the trend in the data and uses the mean at the end of the period, the flow estimates are higher for each AEP as shown in Table 4.1. (See inset on subsequent page for computation details.) The lower floods like the 0.50 AEP discharge increase more (67 percent increase) compared to the larger floods such as the 0.01 AEP discharge (16 percent increase). This example illustrates that nonstationarity does not necessarily affect all AEP flood discharges by the same proportion.

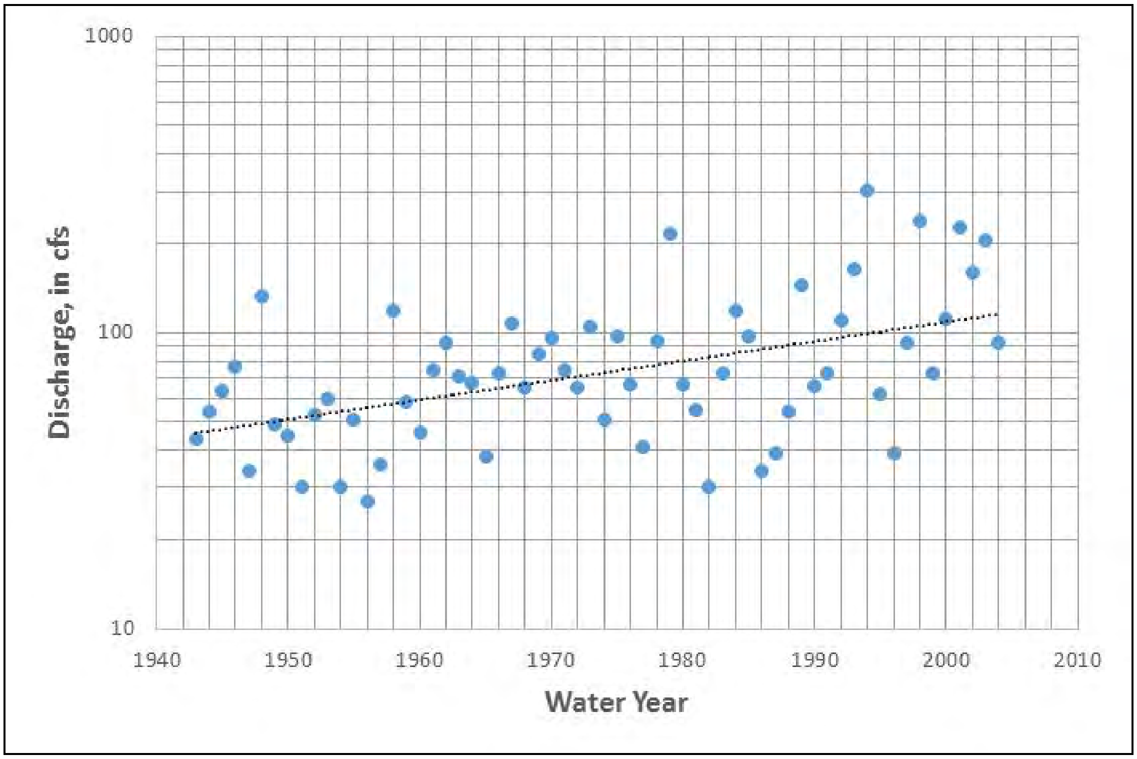

Figure 4.9. Annual peak discharges for Stockley Branch at Stockley, Delaware.

Table 4.1. Flood frequency estimates with and without adjusting for the mean.

AEP	Estimate Without Adjusting for Nonstationarity (ft^3/s)	Estimate Adjusting for Nonstationarity (ft^3/s)
0.50	70	120
0.10	150	220
0.01	320	370

It is important to recognize that this type of statistical analysis does not require identification of the specific cause(s) of the trend. The adjusted statistics are valid for the current point in time. Assuming the trend will continue into the future cannot be supported without knowing the source of the trend. In this example, the trend results from increased precipitation near the end of the record; there are no land use changes in the watershed during the period of record. It is not reasonable to extrapolate the trend beyond the observed data. However, if it can be determined that the higher precipitation is the result of larger climate trends rather than climatic variability extrapolation might be justified. As stated in Read and Vogel (2015), the trend should only be extrapolated if there is some physically meaningful covariate (like a measure of land use or climate) that defines the trend into the future.

This analysis only provides an estimate of the changes in mean values over time (does not include the standard deviation). Vogel *et al*. (2011) and Read and Vogel (2015) indicate that there is little change in the coefficient of variation (standard deviation divided by the mean) of flood data under nonstationary conditions so using a time varying mean also accounts for the variation in the standard deviation.

Implementation Example of the Time-varying Mean

The trend line in Figure 4.9 *represents the logarithmic mean of the annual peak discharges showing an increase with time. The equation of the line is:*

$$log_{10}(Q) = 1.65514 + 0.00658t$$

where:

Q = *annual peak flow, ft*^{3}*/s*
t = *time since 1943, years*

The slope of the trend line (0.00658) implies a 0.66 percent increase in the annual peak flow per year. The slope is statistically significant at the 5-percent significance level. (The p-value is less than 0.0001 indicating a strong upward trend.).

The previous equation can be rewritten as follows:

$$log_{10}(Q) = \overline{LQ} + 0.00658\left(t - \frac{n+1}{2}\right)$$

where:

$\overline{LQ}$ = *mean of the logarithms (1.86231 log units)*
n = *number of years of record (62 in the example)*

The ratio (n+1)/2 represents the average number of years in the record.

The equation for estimating the x-percent AEP flood discharge assuming the logarithms are Pearson Type III distributed is:

$$log_{10}(Q_x) = \overline{LQ} + 0.00658\left(t - \frac{n+1}{2}\right) + K_x\,S$$

where:

Q_x = *x-percent AEP flood discharge*
K_x = *frequency factor for the x-percent AEP and skew (0.0635 in this example)*
S = *skew estimated from the logarithmic residuals (0.2106 in this example)*

Using above equation and a table of the Pearson Type III frequency factors (Table 4.13 in HDS 2), the analyst can compute the adjusted flows in Table 4.1 as well as other AEPs.

4.4. Projecting Flood Frequency

Under stationarity, the planner/designer uses historical data (sometimes adjusted as described in the previous sections) to project flood frequencies over the life of a plan or project. With nonstationarity caused by LULC, climate, or other factors, adjustments to the approach are necessary so that projects are not under-designed if the trends result in increasing flows or, over-designed if trends result in decreasing flows.

Local and regional planning agencies may have completed projections of future LULC. However, these projections may not be explicit about the time frame or probability of the projections. The Integrated Climate and Land-Use Scenarios (ICLUS) project investigated the relation between the impacts of land-use change and climate change (USEPA 2009). The results include impervious area estimates for 2050 and 2100 for several emission scenarios. The data are spatially disaggregated at 1-km^2 grids. These data may be useful for estimating future impervious area.

Climate modeling provides projections of future precipitation. Chapter 5 describes the methods and results of climate modeling efforts. The following section briefly discusses selected strategies applicable to projecting flood frequency using rainfall/runoff modeling and statistical methods.

4.4.1. Rainfall/Runoff Modeling

Rainfall/runoff modeling routinely addresses LULC changes by modifying input variables such as the rational method runoff coefficient or time of concentration to reflect the anticipated future conditions. However, predictions of future LULC conditions add an unquantified degree of uncertainty to the design process. This is simply part of the design process at this stage of development of the technology.

Rainfall/runoff models include precipitation as an input variable. Projections of changes to precipitation generally rely on the use of downscaled global climate models (see Chapter 5). These projections also add uncertainty to the design process. The key questions are what effects does climate change have on precipitation frequency curves? Can and how do downscaled global climate models provide precipitation data for hydrologic design?

Chapter 7 (Analysis Framework) provides guidance on how climate projections of precipitation can be incorporated into hydrologic design processes. Chapter 8 (Case Studies) provides examples of applications using these data and techniques.

4.4.2. Statistical Modeling

Statistical methods based on measured peak discharges inherently assume that the underlying climate characteristics are stationary. For direct gage analysis, the LPIII method produces statistical parameters (mean, standard deviation, and skew) based on historical data. Section 4.3.2.3 describes a process for frequency analysis when the mean is varying with time. There is a need for developing tools to estimate the future mean and the other statistical parameters under nonstationary conditions.

Designers frequently use regional regression equations to estimate design discharges for bridges and culverts. Their use for projecting design discharges with changes in LULC or climate is limited primarily because most current regional regression equations do not include parameters representing LULC or climate. When they do include such parameters, for example mean annual precipitation, the hydrologic designer should recall that to use any regional regression equation, the parameter values should be within the range of values used to develop the equation.

In addition, the conditions to which the equations are applied should be representative of the conditions from which the underlying data were collected. Under nonstationary conditions, the future is different from the past possibly leading to the conclusion that regional regression equations should not be used for future projections. However, one should also not assume that all hydrologic relationships are restructured under nonstationary conditions and that regional regression equations can never be used for future projections. They can be useful engineering tools for planning, analysis and design purposes.

Other national and regional regression equations are being developed and explored for use in projecting future discharges under nonstationary conditions. For example, a consultant team developed nationwide regression equations for the 100-year (and other return period) flood intended to incorporate changing precipitation from climate change and land use changes (Thomas *et al*. 2010, Kollat *et al.* 2012, AECOM 2013). The consultant team used the equations as part of a nationwide planning study recognizing that the equations were not appropriate for design purposes. The North Jersey Transportation Planning Authority used these national equations to estimate the extent to which their transportation assets (roads and rail) might be located in projected floodplain areas as part of their Climate Change Vulnerability and Risk Assessment (North Jersey Transportation Planning Authority 2012).

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Chapter 5. Climate Modeling

The climate models used to represent atmospheric physics and the connections between the atmosphere, the land surface, the sea surface, and the ice of the arctic regions continue to develop. The United States and other nations have made significant investments in climate modeling because of concern regarding historical trends that show increasing concentrations of greenhouse gases and global temperatures. Figure 5.1 presents a time series of CO_2 concentration and global average annual temperature from about 1880 to 2014 (Walsh *et al.* 2014). Both CO_2 concentration and global temperature have been increasing since the late 1800s. Global annual average temperature (as measured over both land and oceans) has increased by more than 1.5°F (0.8°C) since 1880 (through 2012). The horizontal line represents the long-term average. The curved line shows atmospheric carbon dioxide (CO_2) concentration in parts per million (ppm). While there is a clear long-term global warming trend, some years do not show a temperature increase relative to the previous year, while other years show greater changes. These year-to-year fluctuations in temperature result from natural processes, such as the effects of El Niño, La Niña, and volcanic eruptions.

For more information on climate change science and projected changes in climate, please see:

Climate Change Impacts in the United States: The Third National Climate Assessment (2014).

Fifth Assessment Report of the Intergovernmental Panel on Climate Change (2013, 2014) [includes multiple reports on climate science, adaptation and vulnerability, and Greenhouse gas mitigation].

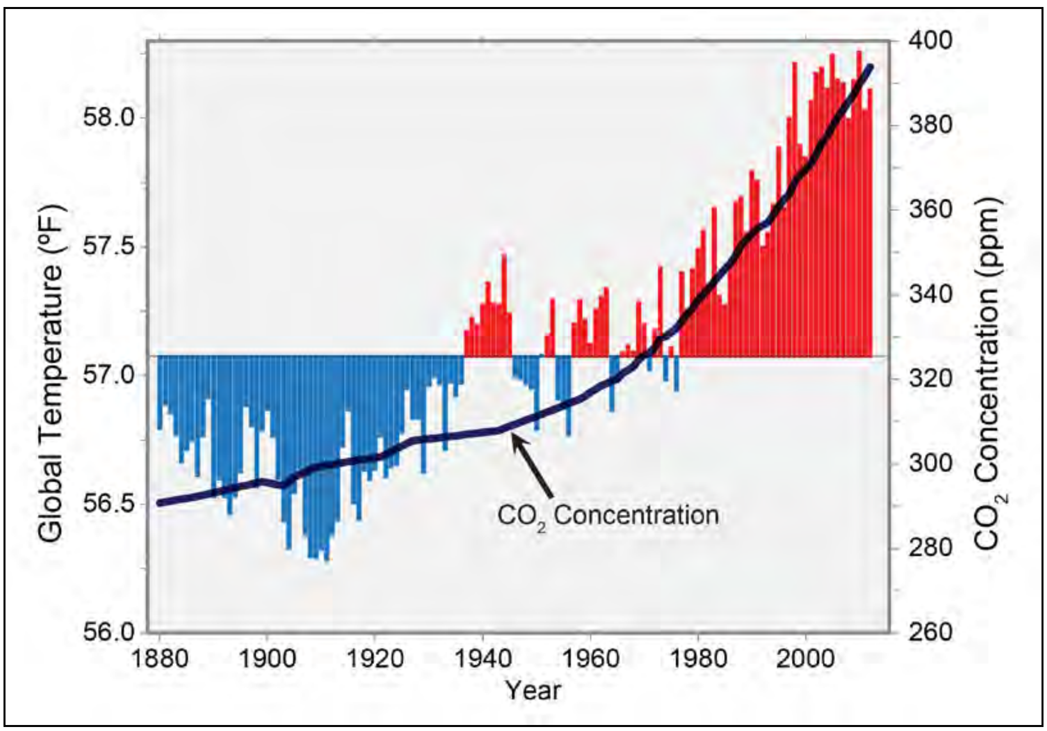

Figure 5.1. Global CO_2 concentrations and annual average temperature.

As shown in Figure 5.2, development of climate projections useful for hydrologic and other applications requires a number of distinct activities including the development of emissions scenarios, development of other input data, application of global climate models, and then downscaling the data to an appropriate temporal and spatial scale. This chapter presents an overview of climate modeling, emission scenarios, and downscaling, while highlighting several tools for access of available climate change projections.

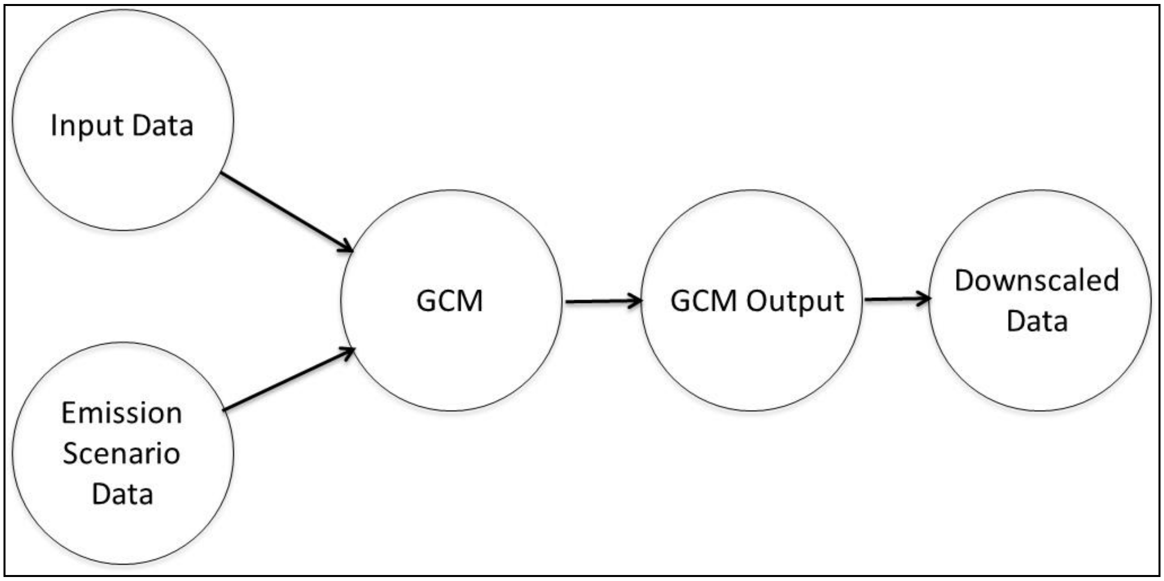

Figure 5.2. The relation between emissions scenarios, GCMs, and downscaling.

5.1. Global Climate Models

Climate models are complex numerical models used to examine the interactions of the atmosphere, land surface, oceans, and arctic ice. Developers of climate models use physical principles to describe the relations between the atmosphere, land surface, and sea ice. These physical principles are then approximated using numerical methods so that they can be solved by computers. The resulting numerical models are called General Circulation Models or Global Climate Models (GCMs). Climate scientists use GCMs to track the movement of the atmosphere, the distribution of water vapor, movement of energy and momentum, and interaction between the atmosphere, land processes, ocean processes, and sea ice. Different models include different components.

Climate scientists use the term “forcing” to describe real or potential changes to the climate system that might result in changes to global (or regional) climate. Because GCMs model the gross processes that comprise climate, they are useful for examining the effect of forcings on the climate trajectory in space and time. ***Radiative forcing***, measured in watts per square meter (W/m^2), is a measure of the change in the energy balance on the earth caused by increases in the concentration of greenhouse gasses (GHGs), such as carbon dioxide (CO_2) and methane (CH_4). CO_2 is the main anthropogenic greenhouse gas and measurements for other GHGs are generally reported in terms of CO_2 equivalent units, or CO_2eq. Section 5.2 discusses ***emissions scenarios*** describing alternative projected changes in GHGs.

These tools operate over a solution domain that encompasses the space from the Earth’s surface to an elevation that represents the climatologically active portion of the atmosphere. The horizontal spatial resolution continues to improve with grid cells of 311 miles (500 km) on a side typical in 1990 to grid cells of 68 miles (110 km) typical in 2007. Vertical resolution has also improved ranging from models representing the oceans as a single layer and the atmosphere in 10 layers to models that represent the oceans with 30 layers and the atmosphere with 30 layers (UCAR 2016).

Because the spatial and temporal scales of GCM computations are relatively large, results are not directly useful to engineers and scientists who work at much smaller spatial and temporal scales. Therefore, additional analytical tools are needed (such as post-processing computer programs) to adapt GCM output for use by transportation engineers and planners. This ***downscaling*** is discussed further in Section 5.3.

The output from GCMs generally requires substantial post-processing to summarize model outputs. First, large differences can exist between outputs from different GCMs even if using the same input. That is, the raw output from one GCM might differ substantially from the output of another GCM at the point or area of interest using the same initial conditions, boundary conditions, and assumptions about changes in GHG concentrations or other climate forcing variables. These differences result from differences in assumptions and formulations used for different GCMs. Therefore, climate scientists generally examine output from a range or ***ensemble*** of GCMs and GCM output. That is, they often consider the average and range of results from a suite of GCMs (an ensemble result) to improve the robustness of results for a climate change scenario. In addition, climate scientists examine the outcomes from different climate change scenarios – each with its own set of assumptions - to improve their understanding of the range of possible futures.

In addition, climate modelers use ***hindcasting*** (computation of periods of record for which measured meteorological data exist) and examination of model equations to validate the models. Hindcasting is also useful for ***downscaling*** from the relatively large solution domains of GCMs to smaller areas so that end-users can use results from climate modeling to assess potential impacts for studies or projects. An example of the use of downscaled results would be assessment of potential climate change on transportation infrastructure.

5.2. Emissions Scenarios

Climate scientists expect the magnitude of the ***forcings*** to increase with increases in GHG concentrations. However, the magnitude of increase in GHGs and whether the increase is bounded or unbounded is unknown. Therefore, climate modelers use ***emissions scenarios*** based on a variety of assumptions to project future levels of GHGs and use this information to prepare input to GCMs for modeling potential climate change. The Special Report on Emission Scenarios *(SRES)* documents the first formal set of emissions scenarios (Nakicenovic *et al.* 2000, Melillo *et al.* 2014). Representative Concentration Pathways (RCPs) are a second set of emissions scenarios (van Vuuren *et al.* 2011, IPCC 2013, Melillo *et al.* 2014).

Figure 5.3 summarizes projected global temperature changes from a range of GCMs using a subset of SRES scenarios (on the left) and RCP scenarios (on the right) (Walsh *et al.* 2014). Each scenario represents different amounts of heat-trapping gases released into the atmosphere resulting in projected increases in Earth's temperature. In the figure, each line represents a central estimate of global average temperature rise (relative to the 1901-1960 average) for a specific emissions scenario. Shading indicates the range (5th to 95th percentile) of results from a suite of climate models. Bars to the right of each panel represent projections in 2099 for additional emissions pathways.

In all cases, temperatures are expected to rise, although the difference between lower and higher emissions pathways is substantial. Differences in modeling outcomes reflect uncertainty in both the scientific tools and data as well as the uncertainty associated with the emissions scenarios (see box inset). The following sections provide more detailed descriptions of the SRES and RCP scenarios.

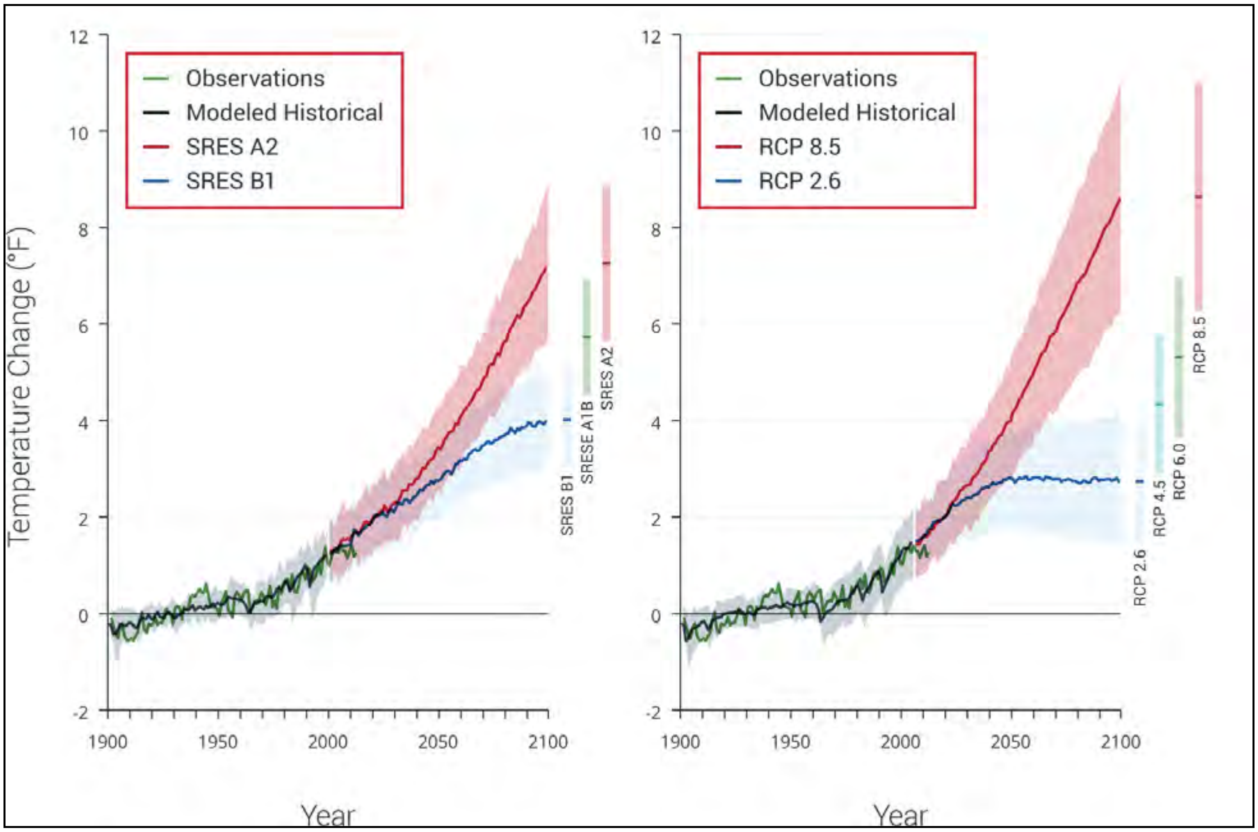

Figure 5.3. Projected global temperature changes for different emissions scenarios.

Scientific versus Scenario Uncertainty

At least two types of uncertainty involved in projecting future climate are scenario and scientific uncertainty. Scientific uncertainty applies to data collection and models and scenario uncertain applies to development and selection of emissions scenarios. According to Hayhoe and Stoner (2012) scenario uncertainty is very different, and entirely distinct, from scientific uncertainty. Scientific uncertainty can be reduced through coordinated observational programs and improved physical modeling. Scenario uncertainty arises due to our fundamental inability to predict future changes in human behavior. Scenario uncertainty can only be reduced by the passing of time, as certain choices (such as depletion of a non-renewable resource or implementation of an emissions control policy) eliminate or render certain options less likely.

5.2.1. SRES Scenario Set

The SRES scenario set is a suite of climate change projections for climate variables such as average annual temperature, seasonal precipitation, and others. A set of scenarios was developed so that comparison between outputs from the GCMs used for climate change projections would have a common basis for analyzing mitigation options and for communication. The SRES emission scenarios include a combination of socio-economic "stories" and assumptions about technological change during the 21st century. Climate researchers use socio-economic and emission scenarios to provide plausible descriptions of how the future may evolve with respect to a range of variables including socio-economic change, technological

The SRES Storylines

The A1 storyline and scenario family comprise a future world of rapid economic growth, peak global population by mid-century, followed by a declining global population and rapid introduction of new and more efficient technologies. Major underlying themes are convergence of economic and technology factors among regions, capacity building, and increased cultural and social interactions, with substantial reduction in regional differences in per capita income. From the A1 storyline, three groups of scenarios were developed: fossil fuel intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

The A2 storyline and scenario family describes a heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge slowly, which results in continuously increasing global population. Economic development is regionally oriented. Per capita economic growth and technological change are assumed to be fragmented and proceed more slowly than in other storylines.

The B1 storyline and scenario family presumes a convergent world with the global population of the A1 storyline. The B1 storyline differs from the A1 storyline with rapid change in economic structure toward a service and information economy, with commensurate reduction in use of material resources and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline and scenario family comprises a world emphasis on local solutions to economic, social, and environmental sustainability. The B2 world has a continuously increasing global population, at a rate less than the A2 storyline, with intermediate levels of economic development and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, the emphasis is that these changes occur on local and regional levels.

change, energy and land use, and emissions of greenhouse gases and air pollutants. Climate modelers use these descriptions as input for climate model experiments with approximately 25 different GCMs. Table 5.1 lists a subset of SRES scenarios (based on Swart *et al.* 2002) commonly used by the climate science community including for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007). As a reference point, a current estimate for global carbon dioxide concentration as of the end of 2015 was about 400 ppm (NOAA 2016).

Table 5.1. Six SRES illustrative scenarios and the stabilization scenarios they most resemble.

SRES Illustrative Scenario	Description of Emissions	Surrogate Stabilization Scenario (parts per million CO_2)
A1FI	High end of SRES range	Does not stabilize
A2	High case	Does not stabilize
A1B	Intermediate case	750 ppm
A1T	Intermediate/low case	650 ppm
B2	Intermediate/low case	650 ppm
B1	Low end of SRES range	550 ppm

For the higher emission scenarios, carbon dioxide concentrations do not stabilize within the period covered by the scenario. For example, carbon dioxide concentration for the A1FI and A2 scenarios do not stabilize, but are expected to continue to increase with time. Therefore, one expects that global heating will continue under these scenarios. Although heating will increase under these scenarios, the effects on precipitation is not so clear. In some regions of the country, average annual precipitation may increase while in others it may decrease. The effects on the frequency and intensity of storms will also vary regionally.

In contrast, the carbon dioxide concentration for other scenarios reaches an ultimate value ranging from 550 to 750 ppm. For example, the SRES B1 scenario, constructed with the assumption that carbon dioxide emissions will be mitigated, anticipates carbon dioxide concentration will stabilize at 550 ppm. Other scenarios in the A and B families anticipate carbon dioxide concentration to stabilize between 650 and 750 ppm. These scenarios represent a middle track for global climate change.

5.2.2. Representative Concentration Pathways (RCP) Scenario Set

GCM experiments included in the Fifth Assessment Report (IPCC 2013) were based on a newer set of standard emission scenarios: the Representative Concentration Pathway (RCP) emissions scenarios (Taylor *et al*. 2012). The entire issue of *Climatic Change* in which the Taylor article appears (Volume 109, Issue 1) comprises the documentation for the RCPs currently used for modeling potential future climate scenarios. Particular objectives of the RCP emissions scenarios are to:

- evaluate model performance in simulations of the recent past,
- provide future estimates of climate on two time scales — near term (out to about 2035) and long-term (out to 2100 and beyond), and
- understand or explore factors contributing to differences in model projections, including key feedbacks, such as those involving clouds and the carbon cycle.

GCM experiments from approximately 29 GCMs for the Fifth Assessment Report are based on the Representative Concentration Pathway (RCP) emissions scenarios (Taylor *et al*. 2012). The RCP suite of emission scenarios were informed by the results from the SRES scenarios and were developed to provide more detailed information for operating the current generation of GCMs. The RCP scenarios were designed to incorporate potential changes in climate policy and the effects of possible adaptation strategies. The SRES scenarios did not address these aspects. Addition of climate policy and adaptation strategies was intended to facilitate evaluation of policy changes including their costs and benefits.

The representative concentration pathways presented by van Vuuren *et al*. (2011) are summarized in Table 5.2 including the publication in which the RCP was first described. Elements of Table 5.2 that are of interest to hydrologists and highway engineers are the ultimate carbon dioxide concentrations (and resulting expected heating), which range from 490 ppm to 1,370 ppm carbon dioxide by year 2100. RCP 8.5 is the most conservative (greatest heating) and RCP 2.6 is the least (least heating). Wayne (2013) provides a good description of RCPs at http://www.skepticalscience.com/rcp.php?t=2.

Figure 5.4 summarizes the potential impact of climate change on precipitation for two RCPs (Walsh *et al.* 2014). The top panels show simulated changes in the average amount of precipitation falling on the wettest day of the year for the period 2070 to 2099 as compared to 1971 to 2000 under a scenario that assumes rapid reductions in emissions (RCP 2.6) and one that assumes continued emissions increases (RCP 8.5). The bottom panels show simulated changes in the annual maximum number of consecutive dry days (days receiving less than

0.04 inches (1 mm) of precipitation) under the same two scenarios. Stippling indicates areas where changes are consistent among at least 80 percent of the models used in this analysis.

Table 5.2. Representative concentration pathways.

RCP	Description	Publication
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 equivalent) by 2100.	Riahi *et al*. 2007
RCP 6.0	Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2 equivalent) at stabilization after 2100	Fujino *et al*. 2006 Hijioka *et al*. 2008
RCP 4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 equivalent) at stabilization after 2100	Clarke *et al*. 2007 Smith and Wigley 2006 Wise *et al*. 2009
RCP 2.6	Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2 equivalent) before 2100 and then decline (the selected pathway declines to 2.6 W/m^2 by 2100).	van Vuuren *et al*. 2007 van Vuuren *et al*. 2006

5.3. Downscaling

GCMs are numerical models that operate with geographically large computational cells. These cells comprise the solution domain of the GCM and are analogous to the distance between cross sections in a one-dimensional hydraulic model or the length and width of a computational cell of a two-dimensional hydraulic model. Climate models produce results at a scale of approximately 120 or 190 miles on a side, which limits the ability of models to provide results for use at the project or local scale (Hayhoe and Stoner 2012).

At such a large scale, climate models do not generally produce results in sufficient detail necessary to inform project development and design. In addition, GCM structures do not generally include the effects of mountains and other orographic influences that affect climate at the regional scale.

As a result, two ***downscaling*** approaches have been developed to provide climate change data at a scale useful to engineers and others. One procedure is ***dynamic downscaling***, which depends on a Regional Climate Model (RCM) with computational cells that are much smaller than those used in a GCM. The other is ***statistical downscaling***, which depends on development of a statistical relation between observed local climate measurements (at meteorological stations) and hindcast GCM output.

Dynamic downscaling data are developed using RCMs, which are climate models that are operated using solution domains that are much smaller than those used by GCMs (the scale varies, but cell size is generally less than 60 miles). Because the solution domains are smaller, additional physics can be included in the model formulation than in the larger domains of the GCMs.

Statistical downscaling is a process of using statistics to relate GCM output to historical measurements of climate variables of interest. Once established, the statistical relations can be used to generate estimates needed for hydrologic computations. There are several statistical downscaling techniques, including Bias Corrected Constructed Analogs (BCCA), Asynchronous Regional Regression Model (ARRM), and Bias Corrected Spatially Downscaled (BCSD).

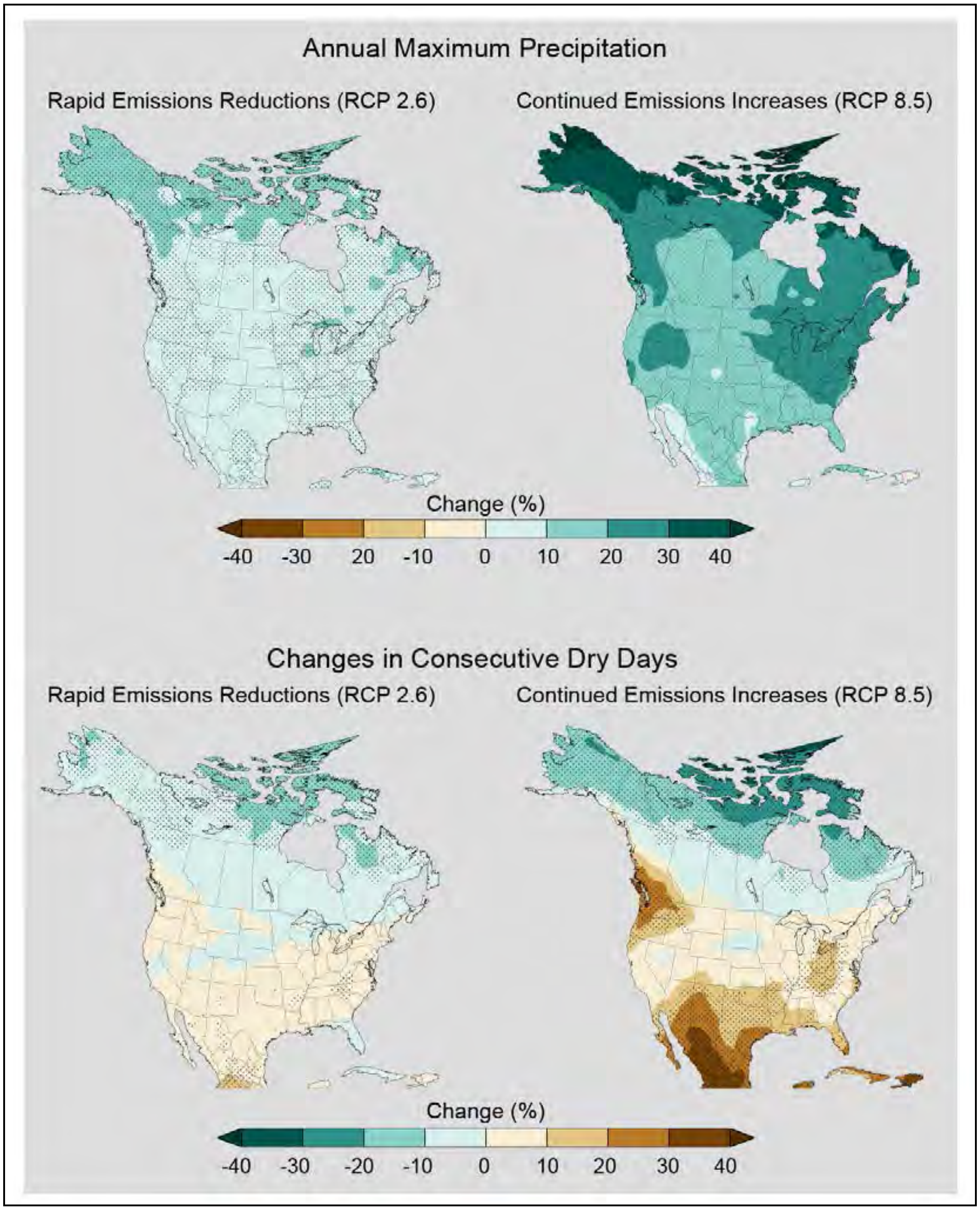

Figure 5.4. Precipitation projections for two RCPs.

Bias refers to the differences between historical period GCM simulations or downscaled data and measured observations. Matching specific historical events is not important because GCMs are not designed to produce specific events. However, the hindcast (historical period) output should produce similar statistics (means, variances, and trends) to those from the measured record. Statistically downscaled (and bias-corrected) climate projections are hosted by the Lawrence Livermore Laboratory as part of the Coupled Model Intercomparison Project (CMIP), a collaboration between a number of government agencies and universities.

Natural Variability, Scientific Uncertainty, and Scenario Uncertainty

Natural variability adds further complexity to the challenges of scientific and scenario uncertainty. As described by Hayhoe and Stoner (2012) over timescales of years to several decades, natural chaotic variability is the most important source of uncertainty. By mid-century, scientific uncertainty is the largest contributor to the range in projected temperature and precipitation changes. By the end of the century, scenario uncertainty is most important for temperature projections, while model uncertainty continues as the dominant source of uncertainty in precipitation.

There are several sources of downscaled climate projections and the options will likely increase. At this time, FHWA notes the following data clearinghouses:

- the Downscaled CMIP3 and CMIP5 Climate and Hydrology Predictions (DCHP) (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html#Welcome),
- USGS Geo Data Portal (http://cida.usgs.gov/gdp/),
- the Coordinated Regional Climate Downscaling Experiment (CORDEX) (https://na-cordex.org), and
- the North American Regional Climate Change Assessment Program (NARCCAP).

FHWA uses and recommends the CMIP data available from **_DCHP_**, though other well vetted data sources may also be used**.** The DCHP is supported by several federal agencies and nongovernmental groups focused on climate change research, including the USACE, the USGS, DOE, Bureau of Reclamation, and the National Center for Atmospheric Research (NCAR). It includes projections for multiple scenarios and models covering the contiguous United States. The site includes daily time step datasets that use the BCCA statistical downscaling process (and monthly projections using the BCSD process). The most detailed spatial scale available is 1/8 degree by 1/8 degree, or roughly 7.5 mile by 7.5 mile (12 km by 12 km) at mid-latitudes.

The Coupled Model Intercomparison Project, Third Phase (CMIP3) was developed as part of the Fourth Intergovernmental Climate Change assessment. CMIP3 comprises downscaled results of projected climate from about 25 GCMs (each with up to 12 experiments) using the SRES A2, A1b, and B1 emissions scenarios. The CMIP3 output data are not continuous in time. The control period for CMIP3 is 1961–2000 and the projected periods vary depending on the SRES scenario modeled.

CMIP Phase 5 (CMIP5) followed CMIP3 beginning in 2008 as part of the Fifth Assessment Report. GCM experiments for the Fifth Assessment Report (developed from output from about 29 GCMs) are based on the four representative concentration pathway (RCP) emissions scenarios (Taylor *et al*. 2012). The CMIP5 dataset contains numerous hindcasts and future projections (Taylor *et al.* 2009, Taylor *et al*. 2012).

The **_USGS Geo Data Portal_** includes downscaled data from a variety of sources. Among other data sets, the portal includes statistically downscaled data using the ARRM process. The USDOT used the ARRM process to develop the climate projections for the Gulf Coast 2 study (FHWA 2013).

The **_NA-CORDEX_** website provides links to dynamically downscaled datasets from a variety of RCMs and RCP scenarios for North America. NA-CORDEX, and CORDEX in general, is primarily sponsored by the World Climate Research Program (WCRP).

The ***NARCCAP*** website houses data based on the SRES A2 emissions scenario. The A2 scenario is not the most conservative of the SRES scenarios, but results in GHG concentrations that are greater than most of the other scenarios in the SRES suite. On the NARCCAP website, the justification for this choice is:

> *"The A2 scenario is at the higher end of the SRES emissions scenarios (but not the highest), and this was preferred because, from an impacts and adaptation point of view, if one can adapt to a larger climate change, then the smaller climate changes of the lower end scenarios can also be adapted to." (Retrieved from http://www.narccap.ucar.edu/about/emissions.html on 29 December 2015.)*

The NARCCAP datasets are based on four GCMs for the general modeling and six RCMs for dynamically downscaled climate data. Model output from two time periods are provided, a hindcast period from 1971–2000 and future period from 2041–2070. The historical period is for validation of model performance for the region of interest and the future period is for assessing the potential for climate change under the SRES A2 scenario. Users can obtain output comprising at least precipitation and temperature with a time step of 3 hours or daily. Other variables are also available. (The NARCCAP website has more detail on the models and output variables.)

5.4. Other Data Sources and Tools

Available data and tools in climate science and modeling continue to expand and evolve. Individuals and groups of collaborators interested in climate change and climate change datasets are increasing their presence on the Internet. For example, Dr. Edwin Maurer hosts a dataset for the contiguous United States and portions of Mexico and Canada based on the CMIP3 experiments (http://www.engr.scu.edu/~emaurer/data.shtml). This dataset, and probably other similar collections, represent datasets developed for specific projects from canonical datasets (such as the CMIP3 and CMIP5 datasets) and it might be tempting for engineers to use such datasets for transportation applications. This situation represents the state of the science in that there are a number of (perhaps many) secondary data sources that represent datasets developed for a specific project or set of projects.

Given the evolutionary nature of climate science, modeling, and data, FHWA recommends that analysts, planners, and designers consult with various organizations with expertise as needed to support project planning and design. These organizations include the:

- FHWA climate adaption website, which includes a range of studies, information, and applications (http://www.fhwa.dot.gov/environment/climate_change/adaptation/),
- state Departments of Environmental Protection (DEP) or Departments of Natural Resources (DNR),
- National Oceanographic and Atmospheric Agency's Regional Climate Services Directors,
- USGS district Water Science Centers,
- USACE district engineering centers,
- University climate science centers (for example, the Climate Impacts Group at the University of Washington),
- Infrastructure and Climate Network (ICNet) (http://theicnet.org/),

- National Center for Atmospheric Research (NCAR), and
- Engineering for Climate Extremes Partnership (ECEP) (http://www.ecep.ucar.edu).

In addition to these resources, FHWA/USDOT has developed two tools to process the daily high/low temperature and daily precipitation projections into useful variables (e.g., annual max 24-hr precipitation) (USDOT 2015). Data retrieved from the DCHP repository for either the CMIP3 or the CMIP5 experiments are input into the FHWA analysis tool, which are Excel spreadsheets available from the Internet at: http://1.usa.gov/1Vr7utH. A large number of output estimates and statistics are available to the end user. Examples include maximum daily temperature, the 95th percentile maximum daily temperature, the 99th percentile maximum daily temperature, the maximum daily precipitation, the 95th percentile daily precipitation, and the 99th percentile daily precipitation. Detailed direction for preparation of input data, analysis, and interpretation of output data are included in the report (USDOT 2015).

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Chapter 6. Risk and Resilience

This chapter explores risk and resilience. ***Risk*** is the product of the probability of an undesirable event and the consequences of the event. Risk provides an overall framework for assessing or analyzing planning and design strategies and decisions. Risk analysis or assessment incorporates the concept of vulnerability and provides some measure of the costs and consequences (monetary and other) associated with damages and performance interruptions associated with the asset vulnerability to facilitate the comparison of alternatives. This chapter also discusses how planners and designers can reduce the vulnerability of transportation assets by evaluating and improving the asset/system resilience. ***Resilience*** is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions (FHWA Order 5520 2014). Planners and designers can enhance resilience by planning, designing, and managing transportation assets to minimize asset sensitivity to damage and to maximize its adaptive capacity.

First, this chapter describes the traditional use of design events including the limitations of that approach. The next subject described is a process of evaluating plans and projects using a more robust range of events. Following this, the chapter provides a discussion of different consequences of exceeding design criteria; noting that not all exceedances are equivalent in terms of risk. Finally, the chapter introduces various adaptation strategies to increase resilience.

6.1. Design Events

In the transportation community, there are two major considerations driving the development of policy governing the specification of design events. First and foremost, the transportation community should ensure public safety. Threats to public safety may come in a direct form, such as the potential for vehicles being washed away by floods and encountering life-threatening situations, or in an indirect way, such as the impediment of emergency services access as a result of out-of-service transportation facilities.

The second major consideration involves the preservation of the transportation asset, that is, the road, culvert, or bridge itself. Even if a transportation asset does not constitute a vital link in the chain of emergency services, damage to, or loss of, an asset may result in a financial loss as well as a loss of utility (economic loss) of the entire facility and inconvenience to the public.

6.1.1. Design Criteria

Typical criteria for designing transportation-related hydraulic assets (e.g. bridges, culverts, channels, or storm drains) are based on a ***design event***. Specifying a design event is a way of balancing risk, costs, and benefits. In some situations, such as bridge scour design, a more severe (lower probability) ***check event*** is also specified. Agency policy and standards generally define the design event based on consideration of the nature of the structure, the roadway, or of the transportation facility served.

The nature of the transportation facility is often a major consideration in setting the design criteria. For example, the consequences of the loss of service (even temporarily) of a principal arterial roadway in a large metropolitan area are more of a burden on the public and risk to public safety than would be a similar loss of service on a remote, rural, local roadway. Thus, the metropolitan arterial would warrant a different treatment under policy than the rural local roadway. Table 6.1 provides an example of the varied AEPs based on the type of roadway and traffic volume (AASHTO 2014).

Table 6.1. Design event selection guidelines.

Roadway Classification*	Exceedance Probability (percent)	Return Period (years)
Interstate, Freeways (Urban/Rural)	2%	50
Principal Arterial	2%	50
Minor Arterial System, ADT>3000 VPD	2%	50
Minor Arterial System, ADT=<3000 VPD	4%	25
Collector System with ADT>3000 VPD	4%	25
Collector System with ADT=<3000 VPD	10%	10
Local Road System	20%-10%	5-10

*Average Daily Traffic (ADT): Vehicles per Day (VPD)

As illustrated in Table 6.1, required or recommended design events are usually specified in policy documents by probability of exceedance, often framed as a value or range of values. One or more critical hydrologic quantities (most often peak discharge, but in some cases runoff volume and peak discharge) corresponding to the target AEP should be estimated, and the structure designed to manage that quantity. The key association between the hydrologic design event and the engineering design of the structure is that for the target quantity, the structure geometry should be designed to accommodate the peak flow in a way consistent with what is stated in policy.

The design event should pass through the facility without significant loss of service or damage. For example, the culvert passing a stream under a road should be designed at the design event so that water does not overtop the road, in accordance with 23 CFR 650. Section 115 of 23 CFR 650 states “Freeboard shall be provided, where practicable, to protect bridge structures from debris- and scour-related failure.” Situations may be encountered where the practicability of designing with freeboard is in doubt, or where overtopping of the roadway at the design discharge may be present a favorable overall risk environment than designing with freeboard.

Traffic volume is usually a key factor in establishing roadway classification. Often measured in terms of average daily traffic (ADT), traffic volume is an important metric of the potential for excessive burden on the public, as well as the risk to public safety, for transportation asset failure. Higher ADT corresponds to potentially higher consequences for failure.

However, traffic is not the only relevant factor. A lack of convenient alternate routes, or a condition of “landlocking,” where no alternative routes exist, contribute to situations where the public or emergency responders may be exposed to risks. However, the mere existence of alternate routes may not guarantee access as these, too, may be impaired by the same flooding event at the same time. Therefore, a local transportation network may warrant analysis as an interdependent system to anticipate critical events involving disruption at multiple locations simultaneously.

6.1.2. Expected Performance over the Design Life

The designer should consider the performance of the project over its ***design life*** given the design criteria. The design life is a reference period over which a project feature is expected to meet a particular service objective (75 years for bridges according to the AASHTO LRFD Bridge Design Specifications). ***Service life*** is the actual period over which the project features provide a given service.

If a designer assumes a reasonably long design life, the likelihood of observing a discharge exceeding that associated with the design event is generally not negligible. For example, if the design AEP for headwater on a culvert on an urban collector is specified in policy as a 10-percent AEP (10-year return period), the risk of that criterion being equaled or exceeded in any given year is 1 in 10, or 10 percent. Over the expected lifetime of the culvert, exceedances of the criterion may occur multiple times. Exceedance is expected under conditions that are defined, and therefore exceedance does not necessarily constitute "failure," although it may result in consequences ranging from inconvenience, to damage, to complete structural failure. Therefore, the designer should consider the consequences of the expected exceedances.

Extending the probability of exceeding a design storm over many features along a roadway or within a geographical area, increases the probability that managing the consequences of exceedances will be required over the design life of a project. Individual projects or locations should be considered in the context of the larger transportation network.

The longer the design life, the greater the risk of such an extreme event occurring during the design life. The probability that a design flood level will be equaled or exceeded at least once during the design life of the project (the probability of occurrence) is,

$$P = 1 - \left(1 - \frac{1}{T}\right)^{n} \tag{6.1}$$

where:

P	=	probability that the design flood level will be equaled or exceeded in *n* years
n	=	design or expected service life, years
T	=	the return period of the design storm, years

This equation is a reduced form of the binomial distribution common in quantitative risk analysis (see HDS 2 Equation 4.81 (McCuen *et al*. 2002)).

For example, consider that the design storm for a transportation asset is the 2-percent AEP (50-year) storm. Therefore, T = 50. If the design life is 75 years, then the probability of occurrence of a flood equaling or exceeding the design flood at least once during the design life is:

$$P = 1 - \left(1 - \frac{1}{50}\right)^{75} = 0.78\ (78\,percent)$$

There is a 78 percent chance that the 50-year flood or greater will occur at least once over a 75 year period. This result is seen in Figure 6.1, which shows a family of lines corresponding to different risk levels expressed as P = probability of occurrence, as a function of T = design return period and n = years of service. Table 6.2 summarizes the same relationship.

Another way to use Figure 6.1 or Table 6.2 is to consider what design storm level is required to attain a given risk level. For example, a designer might seek to design certain critical facilities to reduce the probability of failure to a smaller level than would be required under typical design criteria. For example, say a 5 percent risk of exceeding design criteria over the next 25 years is the goal. Figure 6.1 and Table 6.2 show that the design storm level would have to be T=500 years to attain that low level of probability. (Design storm return periods used for the evaluation of most types of transportation infrastructure range from 10-year to 500-year depending on the type and purpose of the infrastructure.)

Figure 6.1. Probability of occurrence as a function of return period, T, and years of service.

Table 6.2. Probability of extreme event occurrence for various periods.

Length of Service (years)	Frequency – Recurrence Interval				
	10-year	25-year	50-year	100-year	500-year
1	0.10	0.04	0.02	0.01	0.002
10	0.65	0.34	0.18	0.10	0.02
25	0.93	0.64	0.40	0.22	0.05
50	0.99	0.87	0.64	0.39	0.10
75	1.00	0.95	0.78	0.53	0.14
100	1.00	0.98	0.87	0.63	0.18

6.1.3. Evolution of Conditions over the Service Life

Designers typically design drainage structures for a design life that may range from 30 years for some drainage assets to over 100 years for more significant assets such as bridges. Operational service objectives such as the ability to carry a certain volume of traffic rather than specifically the conveyance of streamflow usually drive design life. Although design life and service life are identical at the time of design, transportation managers may extend or shorten service life in ways that designers did not envision during design.

One reason that service life for a transportation asset may be extended beyond the original design life is that the ***functional classification*** of the road or bridge might change. Increased traffic volumes, an increased proportion of truck traffic, or evolving safety standards may result in roadway widening. This may result in the modification, upgrade, or rehabilitation of a drainage structure to extend its service life. Extending the service life of a drainage structure to accommodate changing functional requirements is feasible in many circumstances. Although, certain materials in certain environments may deteriorate, others may last almost indefinitely. In the absence of severe structural deficiency, it is rare for a structure to be completely replaced because the cost is prohibitive. When considering asset modifications to extend service life, designers should revisit the hydrologic and hydraulic performance of the asset.

An important consequence of changing functional classifications is that a reclassification may result in an unrecognized increase in the hydrologic design criteria for the drainage features above that considered in the original design. For example, consider a situation where the original roadway classification at design was as a “secondary” road, but after several years its classification was upgraded to a “primary” road because of increased development and traffic. Its hydrologic design criteria may also increase from perhaps a 25-year flood to a larger 50-year flood. If the only modifications to the culvert are to lengthen it to accommodate a wider road, the culvert might not meet the hydrologic criterion for the new functional classification if the change is not recognized and evaluated. However, after evaluation of costs, traffic disruptions, and hydraulic performance, it may ultimately be acceptable to maintain the current culvert rather than to replace it.

Nonstationarity in land use and climate may also alter the hydraulic risk of drainage structures over their service life. The discharge accommodated by the structure remains the same, but the probability of the occurrence of that discharge changes. Consequently, the risks of flooding also change. The designer should estimate the new return period of the current capacity and evaluate whether the change in risks are acceptable. (See box on the next page for an example. In the example, the probability of experiencing a significant flood over the project lifetime increases from 87 percent to 98 percent.)

6.1.4. Modifying Existing Facilities

Few recent transportation engineering projects involve the design and construction of new roadways and drainage appurtenances on new alignments. The vast majority of transportation projects involve rehabilitation, reconstruction, or expansion of existing facilities. These many thousands of structures exhibit a continuum of ages. In most cases, records are available that reflect the date of construction. The remaining service life may be an influential factor in the management of an existing structure or series of structures. Often, structures adjacent to one another over a considerable length of roadway date to the same original construction project and are of similar age.

For sites where changes in functional classification, watershed or climate nonstationarities, or design criteria are changing, the remaining service life (or revised service life) represents the horizon over which risks to the facility should be evaluated. For example, if 40 year-old bridge with a remaining service life of 60 years requires reassessment, an exercise similar to the example in the previous section can be undertaken using 60-year projections of precipitation. If, however, the current condition of a bridge (according to inspection reports) indicates deterioration or traffic conditions such that the remaining life is not anticipated to be long, prudence may dictate that no analysis is necessary until replacement is considered.

Example: Computing Evolving Risk Over a Service Life

Consider a hypothetical watershed for which climate projections suggest increasing precipitation. For an existing structure that was designed based on a 0.02 AEP (50-year) design event for an estimated 100-year service life, what is the change in the risk profile as a result of the changing conditions should they occur?

The applicable regression equations used for the original design are provided by the USGS and include the mean annual precipitation (MAP) as one of the variables (Asquith and Roussel 2009). The watershed has a drainage area of 100 square miles and the Mean Annual Precipitation (MAP) for the site is 26 inches. The climate projection is that MAP will increase to 32.5 inches, which is within the range of MAP used to develop the equation.

Applying the regression equations for both the existing and future MAP results in the following discharge estimates:

Annual Exceedance Probability	0.5	0.2	0.1	0.04	0.02	0.01
Flow with Current MAP (ft^3/s)	2,280	5,240	7,800	12,000	15,800	20,500
Flow with Future MAP (ft^3/s)	3,110	7,020	10,200	15,500	20,300	26,000

The original 50-year (AEP = 0.02) design flow was 15,800 ft^3/s and the structure was built for that flow. Under future conditions, one can observe that a flow of that magnitude is associated with a 25-year (AEP = 0.04) return period. The projection of climate change, therefore, suggests that a 15,800 ft^3/s (or 15,500 ft^3/s, which is essentially the same) event will come on average twice as frequently. Rather than the design value of once every 50 years on average, it is now expected once every 25 years.

Considering the original service life of the project, the climate changes result in an increase in the probability of an exceedance. Using Equation 6.1 for the original design conditions yields an 87 percent chance of experiencing a flood of 15,800 ft^3/s or greater:

$$P = 1 - \left(1 - \frac{1}{50}\right)^{100} = 0.87$$

For the climate change scenario, the chance of experiencing a flood of 15,800 ft^3/s (15,500 ft^3/s) or greater increases to 98 percent:

$$P = 1 - \left(1 - \frac{1}{25}\right)^{100} = 0.98$$

The structure itself has not changed, but conditions have changed increasing the risks of flooding at the site.

The remaining service life of existing features is an important consideration for developing adaptation strategies under nonstationary conditions. If, for example, a bridge or culvert is 70 years old and is expected to remain in service for another 30 years, the effects of change over those 30 years should be considered, but only minimal action may be warranted. If another bridge or culvert is 20 years old and expected to remain in service for another 80 years, the effects of expected change over that 80 years might be considerably more acute and require a different management strategy than for an older bridge.

An advantage of existing features that have been in place for 20 or more years is that they possess a history of performance. Historical plans and reports, maintenance records, repair project records, historical high water marks, debris lines, photographs in bridge inventory files, and gage data may all be available to indicate actual hydrologic conditions over the life-to-date. These sources of information may provide insight into the “accuracy” of the design discharge/frequency relationship and provide further information with respect to future risk over the remaining service life.

6.2. Evaluating a Range of Events

While evaluating a plan or project for a single design event, and possibly a check event, is standard practice, design engineers may choose to consider a range of events that reflect uncertainty in engineering design methodologies and future scenarios. While not required, considering a range of events is an important tool for considering climate change and extreme events as will be described in Chapter 7.

A primary consideration in designing a drainage structure for resiliency is to understand how it might perform over the service life. It is certain to be subjected to a wide range of flood events. In many cases, it may be valid to assume that at least a few of those events will exceed the design discharge as was demonstrated in the previous section. What may happen, what is expected by the responsible agency, and what is expected by the public in the event of an exceedance are all valid questions for consideration during the design process.

The design event specified by policy and engineering judgment (when policy allows design criteria to range over an interval) should be considered as a target point for specific performance parameters. Merely satisfying these parameters does not end the design process. Performance at larger flows could be assessed. For example, if a structure is designed to accommodate the 25-year event, but the structure lies within a Special Flood Hazard Area as defined by the National Flood Insurance Program, the effect of that structure should be evaluated in the context of the requirements of the base flood (100-year event). This does not necessarily imply that practitioners should design the structure to accommodate the 100-year discharge, but rather that the practitioners should evaluate effects of the proposed structure on the water surface elevation of the BFE and ascertain compliance with NFIP requirements.

Practitioners could also examine structures for performance at lower flow rates commensurate with more frequent flood events. For example, culvert performance is subject to many influencing hydraulic factors such as tailwater depth and barrel slope. While a culvert may perform satisfactorily at the discharge associated with the design event, a larger or smaller discharge may result in undesirable hydraulic conditions. A larger event may cause excessive velocity and the resulting erosion, while a smaller event may result in a velocity that is insufficient to support sediment transport through the reach of influence of the structure. Sediment erosion or deposition could also impair the ability of a culvert to properly perform at the design discharge because of erosion or sedimentation that occurred during preceding, small discharge events.

Evaluating a range of events does not mean creating a plan or designing a project that has no damage associated with that range of events. This is not generally justified on a cost or damage basis. However, by considering this range of events, additional features could be added to a plan or project that enhance its resilience.

The life-cycle cost of a transportation asset consists of several parts. The most visible and evident costs are the design and construction costs. Other costs that are harder to quantify at design are maintenance costs, potential costs to the public in the event of interruption of service, reduction in the value of adjacent land in cases of increased base flood elevation, repair or replacement cost for the structure in the event of damage due to flooding, and repair costs to the adjacent roadway in the event of damage due to flooding. Whereas design and construction costs are certain to be incurred and reasonably predictable in magnitude, many other costs are not only uncertain in magnitude, but uncertain in likelihood.

6.3. Consequences of Exceeding Design Criteria

In Chapter 1 describes a framework for addressing vulnerability that includes the concept of sensitivity (see Figure 1.1). Described as the degree to which an asset is damaged or service interrupted, sensitivity captures the effect on the asset from an extreme event. Because hydrologic design is driven by probabilities that certain events may occur during the design life of a project, planners and designers implicitly and explicitly anticipate and accept that an exceedance of design criteria might occur during the design life. Although these exceedances may be considered a “failure” it is not always the case that negative consequences, in terms of public safety, asset damage or service interruption, will occur. The following sections describe the potential sources of design discharge exceedances and the resulting potential for structural damage.

6.3.1. Design Criteria Exceedance

The hydrologic and hydraulic design of a transportation asset involves estimating the appropriate design flow or flows and configuring the asset to meet specific criteria. When discharges are less than or equal to the design discharge risks are very small or zero. However, this may not be the case when discharges exceed the design discharge. Design discharge exceedances might result from:

- Random, but naturally occurring, high discharge
- Changing conditions in the watershed or climate
- Incorrect estimation of the design discharge

Previously in this chapter, this manual discusses the random nature of flood flows and extreme events and demonstrates that exceedances are possible, even likely, during the design life of an asset. This source of design discharge exceedance is unavoidable and should be considered during the asset design.

Changing conditions in the watershed or climate, as well as incorrect estimation of the design discharge result in a gap between the design discharge and the corresponding exceedance probability. That is, the design does not provide the desired level of risk. Asset managers may only realize such discrepancies through performance of the asset over time, i.e. managers observe more exceedances than are associated with the desired criteria. Asset owners and managers take great care to avoid incorrect estimation of design discharges through the establishment of standard procedures and quality control processes. This manual addresses how designers can expand procedures to anticipate changing conditions in the watershed and changing climate.

Hydraulic responses, for example changes in headwater or frequency of overtopping, can also change over time even if the hydrologic conditions do not change. In some cases, a drainage structure may no longer convey the discharge for which it was designed in the manner in which it was designed. This may result from construction changes, changed ground conditions, or changed channel conditions. For instance, aggradation over time of the reach upstream of a structure and partial obstruction of the structure by aggradation may reduce the conveyance of the structure over time. Vegetation in the channel and overbank areas may change, leading to reduced channel conveyance in the stream above and below the structure. Such evolution at a site may lead to an increased frequency of hydraulic criteria exceedances.

The opposite condition, where the structure conveys a larger discharge than that for which it was designed, does not generally lead to design criteria exceedances, but can be undesirable. Cost of the structure may have exceeded that which would be ideal to meet the design criteria. Excess conveyance and low velocities at low flow depths may result in sediment transport inhibition, leading to long-term stream instability, and increased maintenance costs.

Designers of new transportation assets generally have more options for complying with design criteria than designers of asset retrofits or rehabilitation project. FHWA policy, as reflected in 23 CFR 650.115 provides flexibility for new and retrofit construction by specifying that design “shall be supported by analyses of design alternatives with consideration given to capital costs and risks, and to other economic, engineering, social, and environmental concerns.” For example, particularly for a retrofit or rehabilitation project, allowing overtopping of a roadway or structure may be the least objectionable mode of performance considering risks and other economic, engineering, social, and environmental concerns.

Designers should also recognize that exceedance of a design criterion by itself does not necessarily create a risk to the public or the asset. The risk occurs when the public safety is threatened or the asset is damaged.

6.3.2. Structural Damage

Structural damage involves physical damage to the drainage structure or the transportation facility. This damage may range from minor to catastrophic including collapse of bridges or culverts. Structural damage from flooding may include:

- pavement damage,
- damage to appurtenances such as metal beam guard fence and bridge rail, or signage,
- scour damage
- structure dislodged and moved,
- roadway/embankment damage,
- restriction of hydraulic capacity because of debris accumulation, and
- damage from flooding of nearby structures because of backwater

Structural damage is usually the result of exceeding the hydraulic capacity. Because design criteria exceedances are anticipated as part of the probabilistic design approach, designs are well advised to evaluate the effects of capacity exceedance. By anticipating these exceedances, designers can plan for resistance to or mitigation of damage that will reduce the structural damage and, therefore, reduce the risks. By anticipating exceedances, designer can weigh the risks associated with designing more resilient structures today versus experiencing the risks and structural damage throughout the project design life.

6.4. Adaptation Strategies

Evaluating a range of events, as outlined in Section 6.2, provides more information on conditions that may occur at each site and, therefore, greater opportunity for designing more resilient assets. The following sections provide a discussion of resilience and potential adaptation strategies.

6.4.1. Resilience

Resilience is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions. Resilience and resilient designs are those that can recover from, adjust to, or withstand the exposure to flood events. A resilient plan or project should consider performance of the plan, project, or system over the service life of the project. For example, a resilient bridge design might be one that:

- accommodates the design discharge as planned during the design process,
- survives discharges greatly exceeding the design discharge without catastrophic failure,
- is returned to service quickly without excessive cost or inconvenience to the public when overtopped, or
- is elevated above wave height or water surface sufficiently to prevent damage.

As stated in Section 6.1.2, exceedance of the design discharge over the lifespan of a structure is a reasonable expectation. Policies and engineering should reflect expectation of the exceedance of the design discharge, anticipate the resulting consequences, and balance those consequences against other factors and values to achieve a resilient transportation system. Designing for resilient performance and behavior under adverse conditions does not imply designing for larger discharges (smaller AEP). Resilience implies understanding what happens when events occur that are other than the design flow.

A resilient design may also result from carefully considering approaches to interpreting design standards and balancing the effects of hazards. For example, transportation agencies generally consider that roadway overtopping should be avoided, as implied by the recommendation in 23 CFR 650 that freeboard be provided if practicable. However, the inclusion of practicability as a consideration acknowledges that designing with freeboard, especially for retrofit projects, may not optimize cost, safety, and other considerations. In some cases, allowing short duration overtopping and designing the embankment to withstand overtopping may present a better risk profile, and thus better serve the public, than designs that avoid overtopping at the design discharge. For example, a perched bridge design anticipates embankment overtopping.

Transportation asset managers should craft operational and maintenance strategies with the intent of increasing resilience by resisting damage, where possible, and anticipating it where it is not possible to resist. Preparing to address damage quickly and effectively where and when it occurs are of equal importance to the design of new features and the management of existing ones.

Historically, transportation agencies have relied on risk-based design processes for drainage features to provide a balance between cost of construction and benefits to the public. The probability of events exceeding design criteria was assumed known and unchanging over the design life. Consequently, designers have also assumed that risks are unchanging over the service life. Designing resilient infrastructure begins by recognizing the potential for evolving risks and building in adaptive strategies.

6.4.2. Reducing Vulnerability

As this manual has discussed, the potential for climate and watershed changes may alter the vulnerability of transportation assets to extreme events. Recalling that vulnerability is a function of exposure, sensitivity, and adaptive capacity (see Figure 1.1). It follows, then, that planners and designers can reduce vulnerability by either reducing the sensitivity of the assets to extreme events or by enhancing the adaptive capacity of the assets, or both. To do this, planners and designers should be forward thinking by:

- ***expecting*** that exceedances and overtopping events will occur,
- ***estimating*** how many to expect over an area and a timespan,
- ***anticipating*** the potential effects, and
- ***designing and constructing*** to mitigate detrimental effects.

Strategies for reducing vulnerability during the design of new transportation assets might include:

- designing embankments to resist damage or easy restoration when overtopped, including, where applicable:
  - flexible armoring of approach embankments to prevent erosion,
  - sacrificial embankment sections to enhance flow capacity during extreme flooding,
- “perching” of bridges to engage weir flow over embankments prior to overtopping the bridge itself,
- restraining slab units/bridge spans to prevent lifting of substructure if inundated or subjected to lateral hydraulic loading,
- providing flexible armoring of culvert ends to maintain end conditions,
- evaluating the watershed for debris production potential and planning for debris transport, and
- evaluating stream geomorphology for channel stability and sediment transport characteristics.

Many of these strategies are already standard practices and FHWA encourages broader application of these practices. Many of these are also applicable to retrofitting and rehabilitating existing assets. In addition, there are several strategies that may reduce vulnerability when retrofitting, rehabilitating, or maintaining existing assets. They may include:

- Evaluating how the stream/transportation asset has interacted since construction geomorphologically. Is the stream stable or unstable? Is an extreme event likely to initiate or worsen instability?
- Modifying existing features to resist damage from overtopping. As ongoing maintenance activities and periodic rehabilitation projects occur, asset managers should endeavor to anticipate and mitigate for design exceedances including overtopping events.

- Identifying and prioritizing critical transportation assets because of the associated activities, size, and vulnerability.
- Obtaining or pre-planning easements/access/right-of-way documents for anticipatory or emergency execution to facilitate repairs or temporary detours. This can be coordinated with agencies that perform similar planning for the management of hazardous material routing and spill management.
- Preparing for temporary closures and evaluating alternative routes.
- Preparing contingency plans for equipment and material needed to repair damage after an extreme event expediently.
- Documenting each occurrence of an exceedance/overtopping event to support critical reviews of the effects, organizational reaction, and the public reaction to learn from each incident.

Several of the items on this list are adapted from, and can be coordinated with, complementary hazardous materials response plans and extreme weather evacuation and detour planning. They are characteristic of a strategy for active identification of risks as part of ongoing inspection and maintenance activities.

With changes in both climatic and watershed conditions, an increase in the number of exceedance and overtopping events is likely to be observed. The relatively fixed nature of the discharge accommodated by each individual structure (the design discharge) can be expected to result in an overall increase in the number and severity of exceedance events as time progresses. Resilient designs and resilient retrofits to existing features are a viable strategy for adaptation to that changing likelihood.

Chapter 7. Analysis Framework

This chapter describes suggested levels of analysis for performing risk and vulnerability assessments of riverine transportation infrastructure. The first section describes the levels in a broad context, while subsequent sections provide information that is more specific about the availability and location of products, data, tools, and methodologies appropriate at each level. The guidance in this chapter draws on the ***best actionable engineering and science methods and data*** found in technical publications and reports, accepted manuals and standards, as well as federal or state agency reports. However, the best actionable engineering and science methods and data are constantly changing and recommendations for continued adaptation are included where possible.

FHWA intends for this guidance to support state DOTs and others when they are asked to consider extreme events and climate change in the planning, design, implementation, and management of their transportation assets. This proposed analysis framework is new and FHWA expects that it will evolve over time as experience is gained with the framework and new data and tools become available.

FHWA encourages the management of state DOTs and other transportation organizations to consider how this guidance can be best implemented within their current planning and design protocols and processes. FHWA believes that such management oversight will be critical to providing the planners and engineers within their organization the needed context to apply this framework to specific plans and projects. FHWA does not intent this guidance for all projects and activities, nor is it intended to be a rigid “one-size-fits-all” methodology.

7.1. General Framework

The general framework described in this manual acknowledges that there is uncertainty in the data and models that planners, modelers, and designers use to estimate discharges. Climate and hydrologic processes exhibit patterns and variability that create ***data uncertainty***. Examples of this include nonstationarity in past and future climate as well as changes in land use and other watershed characteristics. Another example of data uncertainty is a lack of certainty regarding future social behavior leading to alternative scenarios for future emissions of greenhouse gases. ***Model uncertainty*** results from the simplifications and approximations in the attempts to construct models to describe real world processes. Model uncertainty applies to climate models and hydrologic models.

The general framework outlined here embraces these sources of uncertainty by explicitly considering them in vulnerability and risk assessments, where possible. Rather than designing for a single design flow, the proposed framework includes processes for considering the resilience of design over a range of possible outcomes that reflect both data and model uncertainty to the extent these can be quantified.

The general framework also recognizes that not all plans and projects merit the same level of analysis. The planning and design team for a project will decide the appropriate level of analysis considering the risks for the plan/project and the hydrologic service life. Evaluation of risk includes the asset criticality, vulnerability, and cost. The following list provides an overview of the levels of analysis:

- **Level 1 – Historical discharges.** At level 1, the design team applies standard hydrologic design techniques based on historical data to estimate the design discharge. In addition, the design team qualitatively considers changes in the estimated design discharge based on possible future changes in land use and climate.

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

This framework applies to not only specific bridge, culvert, or other hydraulic structure projects, but also to plans that may include multiple hydraulic structures and other natural or constructed features. FHWA anticipates that a majority of projects can be addressed using a level 1 analysis. However, the design team is responsible for choosing the appropriate tools and techniques depending on the scope and complexity of the plan or project. Table 7.1 summarizes the types of techniques that might be appropriate for the range of levels of effort. This table provides general guidance, but the design team retains responsibility for the techniques applied for any specific situation considering the technical needs of the project and applicable requirements.

Table 7.1 describes selected rainfall/runoff, statistical, and other techniques that the design team might employ to fulfill the goals of this manual. For example, FHWA recommends that the design team perform a trend analysis on historical data, when available, for level 2 analysis and higher. Trend tests discussed previously in this manual (Section 4.3.1) can be used to make a quantitative assessment. Subsequent sections of this chapter provide detailed explanation of how these tools fit within each level of analysis.

Table 7.2 provides a broad overview of the general types of data needed and potentially available for each level of analysis. The methods and tools chosen for the analyses will determine the required data, but the table indicates when historical and projected data are generally needed. Historical data is required for all levels of analysis. Historical temperature data are only recommended in the higher levels of analysis when a comparison with projected temperature is needed.

The design team should consider programmatic information on possible future conditions at all levels of analysis. This information might include local or state studies of the effects of climate change or LULC changes on flood discharges. It might also include local or state guidance on addressing climate change. Beyond such programmatic information, this manual recommends quantitative projections of climate and LULC for higher levels of analysis. Subsequent sections of this chapter provide detailed explanation of how these data types fit within the levels of analysis.

Table 7.1. Tools versus level of analysis.

Class	Tool	Level 1	Level 2	Level 3	Level 4	Level 5
Rainfall/Runoff	Rational	X	X			
	NRCS Graphical Peak	X	X	X	X	
	Unit Hydrograph	X	X	X	X	X
	Continuous Simulation	X	X	X	X	X
	Advanced Models					X
Statistical	Gaged Discharge Data	X	X			
	Gaged Discharge Data (with trend)		X			
	Regional Regression*	X	X	X	X	X
Other	Programmatic Tools	X	X	X	X	X
	Trend Analysis		X	X	X	X
	Confidence Limits		X	X	X	X
	Comparison of Historical and Projected Precipitation			X	X	X
	Resilience Assessment (Qualitative)	X				
	Resilience Assessment (Quantitative)		X	X	X	X

*Regional regression equations may not be available for levels 4 and 5.

Table 7.2. Data versus level of analysis.

Period	Data	Level 1	Level 2	Level 3	Level 4	Level 5
Historical	Precipitation (D = 24-h)	X	X	X	X	X
	Precipitation (1-h < D < 24-h)	X	X			
	Precipitation (D < 1-h)	X	X			
	Temperature (mean winter)				X	X
	Discharge (annual peak)	X	X	X	X	X
	Land Use/Land Cover	X	X	X	X	X
Projected	Programmatic Information	X	X	X	X	X
	Precipitation (D = 24-h)			X	X	X
	Precipitation (1-h < D < 24-h)				X	X
	Temperature (mean winter)				X	X
	Land Use/Land Cover				X	X

The minimum expertise required for the team responsible for the planning/design of a study or project varies as shown in table 7.3. The importance of specialized expertise in hydrology and climate science grows as the complexity and level of analysis increases. Although a climate scientist/modeler is only called for explicitly in a level 5 analysis, FHWA encourages consultation with climate experts as much as is appropriate for a plan or project whether that consultation is with individual experts or through programmatic information prepared by climate experts with broader application.

Table 7.3. Project team versus level of analysis.

Team Capability	Level 1	Level 2	Level 3	Level 4	Level 5
Designer/Engineer	X	X	X	X	X
Hydrologic Engineer/Modeler		X	X	X	X
Climate Scientist/Modeler					X

The project team bears the responsibility for choosing the appropriate level of analysis for any given situation considering the needs of the project and applicable national, state, and local requirements. Hydrologic service life is one consideration; a project with a longer service life is more likely to be exposed to extreme events and climate change and, therefore, may benefit from a higher level of analysis. Table 7.4 expresses this general guidance.

Table 7.4. Hydrologic service life versus level of analysis.

Service Life	Level 1	Level 2	Level 3	Level 4	Level 5
Less than 30 years	X	X	X	X	
30 to 75 years	X	X	X	X	X
More than 75 years			X	X	X

7.2. Confidence Limits

FHWA recommends one of the tools included in Table 7.1 – confidence limits – for all levels except for level 1. Confidence limits are an important tool for incorporating uncertainty in a hydrologic analysis. Predominant hydrologic design practices focus on a single “most likely” design flow. By contrast, confidence limits define a range of flows that a design team should use to evaluate the resilience of a plan or design. Table 7.5 provides a summary of the suggested confidence intervals based on the anticipated hydrologic service life. As described in Chapter 6, a longer service life provides a greater exposure period, increasing the probability a particular infrastructure element will experience extreme events. A longer service life also provides an extended period where nonstationarities may have a greater effect on project performance. For these reasons, this manual proposes these confidence intervals intended to balance risks and benefits when establishing a range of flows for evaluation and design.

Table 7.5. Confidence intervals based on hydrologic service life.

Hydrologic Service Life (years)	Confidence Interval
Less than 30	38%
Between 30 and 75	68%
Greater than 75	90%

Confidence interval increases as the hydrologic service life increases because the plan or design anticipates that the project must deliver its function over a longer period. However, hydrologic service life is also subject to

Example Confidence Interval

The design flow for a culvert is estimated to be 1,000 ft^3/s and the culvert is expected to have a hydrologic service life of 60 years. Based on the method used to develop this flow, the 68 percent confidence interval is between 700 and 1500 ft^3/s. If the culvert hydrologic service life was expected to be longer, the 90 percent confidence interval for this case is between 500 and 1900 ft^3/s (The size of the confidence interval is unique to every situation.)

uncertainty; therefore, the design team should consider this uncertainty when selecting the appropriate confidence interval.

The general approach for application of confidence limits described in this manual for analyses beyond level 1 is to identify the sources of model and data uncertainty and use that variation to quantify a reasonable range of flow conditions over which to evaluate and design plans and projects to increase their resilience. As this manual explains in the detailed discussions of levels of effort, quantitative estimates of all, or even most, sources of uncertainty are not available. Some modeling tools and data sources include uncertainty estimates while others do not.

For those situations where multiple sources of uncertainty are available it is critical for the design team to analyze them cumulatively so that the resulting flow range is consistent with the desired confidence interval as described in Table 7.5. For example, assume that the 90 percent confidence interval is appropriate for a given project and two sources of uncertainty have been quantified. The design team may choose to consider the joint effect of these two sources of uncertainty in such a way that the combined uncertainty results in flows that represent the 90 percent confidence limits.

One way of accomplishing this is to perform a Monte Carlo analysis using the respective distributions of the two sources of uncertainty. (These are likely not the only sources of uncertainty, but may be the only ones that can be quantified.)

Alternatively, the design team could consider three different scenarios for computing the confidence limits:

- consider only the uncertainty from the first source at a 90 percent confidence level and assume no uncertainty for the second source,
- consider only the uncertainty from the second source at a 90 percent confidence level and assume no uncertainty for the first source, and
- consider the joint probability resulting in a cumulative 90 percent confidence interval.

An example of the latter scenario would be to take the 56 percent confidence interval for both sources of uncertainty. For a 56 percent confidence interval, the upper limit is 78 percent and the lower limit of the interval is 22 percent. The probability of exceeding the joint behavior of both distributions is (1-0.78) x (1-0.78) = 0.05 or 5 percent. A five percent probability of exceedance corresponds to the 95 upper confidence limit, which is the upper limit for the 90 percent confidence interval.

Depending on the importance of, and risks associated with the plan or project, the design team may decide to examine multiple combinations of uncertainty, as described above, or use Monte Carlo analysis when multiple sources of uncertainty are quantifiable. When using the former approach, the design team would use the combination producing the largest discharge range for the given confidence limit for subsequent analyses. For many projects, such detail will not be necessary and that is reflected in the range of levels of analysis FHWA provides in this framework.

When analyzing multiple sources of uncertainty, a common error is sequentially, rather than cumulatively, considering the uncertainty ranges. Using the same example, if the 5 percent exceedance value for the first source of uncertainty is sequentially combined with the 5 percent exceedance value for the second source of uncertainty the combined exceedance probability is 0.05 x 0.05 = 0.0025 or 0.25 percent. This exceedance probability is associated with the 99.5 percent confidence interval, which would be a much larger – and much more conservative – range of discharges to assess than the 90 percent confidence interval. Therefore, the design team should evaluate multiple sources of uncertainty so that their cumulative effect is to satisfy the selected confidence interval. Later sections of this chapter describe the application of confidence limits in each level of analysis.

7.3. Downscaled Climate Data

Table 7.2 provided an overview of the data needs by level of analysis. Levels 3 through 5 use projected precipitation and, in some analyses, projected temperature. As described in Chapter 5, the design team may obtain projections of precipitation and temperature data from a variety of sources that host downscaled climate modeling results.

The selection of GCMs, emission scenarios, and downscaling techniques is challenging for most end users of climate change projections. Selection may involve policy as well as technical considerations. For example, in some countries, policy mandates the use of particular scenarios or sets of results (often worst-case scenarios). A state DOT might consult a climate science expert for assistance in determining which GCM or GCM ensemble is most representative of the region of interest. The objective of such consultation could be to establish appropriate GCMs and emission scenarios either at the project level or for programmatic use.

The temptation might be to select those scenarios that result in the greatest increase in precipitation or temperature, whichever is critical to system analysis. However, those scenarios are associated with a risk of overestimating the effects of climate change. Alternatively, use of emission scenarios (and resulting climate change projections) that provide the least increase (or perhaps a decrease) in precipitation or temperature are associated with risk of underestimating the effects of climate change.

For temperature related variables, generally speaking, the greater the concentration of GHGs, the worse/higher the projection of temperature change. For precipitation, however, the greater GHG concentrations might not translate into the greatest increase in precipitation projections. The processes driving change in precipitation are more complicated and the range of precipitation results might be quite broad, with some models projecting decreases while others projecting increases for the same scenario.

FHWA recommends the downscaled climate projections (CMIP5) from the DCHP database, or an equivalent source, for the following reasons:

- the data include a wide variety of GCMs and a range of emission scenarios,
- the data are curated by a credible collaboration of federal agencies, and
- the website provides easy access to the data and facilitates downloads based on user-selected parameters.

The US DOT CMIP Climate Data Processing Tool User's Guide (US DOT 2015) provides straightforward instructions for downloading and processing downscaled climate projections from the DCHP website. Following these instructions yields a comma-separated values (csv) file with daily precipitation and temperature values. FHWA does not preclude the use of other data sources, but the US DOT CMIP Climate Data Processing Tool only works for the DCHP database.

In addition to the instructions in the User's Guide for the Tool, the design team also should decide the following:

- How many 1/8 x 1/8 degree (approximately 12 km x12 km) cells of data to download?
- Whether to use CMIP3 or CMIP5 data?

- Which emission scenario(s) to use?
- Which GCMs to use?

The Tool averages across up to four grid cells when calculating various precipitation and temperature variables. FHWA recommends using multiple grid cells. Each cell covers approximately 56 square miles. For large watersheds, the design team should download all cells required to cover the watershed. For small watersheds, the design team should download no less than four cells to avoid unrepresentative results that might occur when relying on a single cell.

Use of the Tool might not be the most efficient approach for downloading large numbers of cells for large watersheds. An alternative is to develop custom Network Common Data Form (NetCDF) tools to download from the DCHP database. NetCDF is a set of software libraries and data formats that support the creation, access, and sharing of array-oriented scientific data such as the DCHP data. Unidata, which is a part of the University Corporation for Atmospheric Research (UCAR) Community Programs (UCP), developed and maintains NetCDF (Unidata 2016).

With respect to CMIP3 or CMIP5 data, the CMIP5 data will be more useful for many users for multiple reasons. The CMIP5 data represents a continuous series of daily projections through the year 2100, while the CMIP3 dataset has gaps. The CMIP5 data are based on more recent emission scenarios, more recent GCM simulations (and updated GCMs), and may include improvements in downscaling techniques.

As described earlier, emissions scenarios attempt to anticipate human behavior, economic activity, and public policy decisions. It is difficult, if not impossible, to apply probabilities to such projections. The inability to know what the future emissions trajectory will be is another source of uncertainty. For the CMIP5 data, four emission scenarios (RCPs) are available through the DCHP: 1) RCP 2.6, 2) RCP 4.5, 3) RCP 6.0, and 4) RCP 8.5. As described in Chapter 5, lower numbers correspond to lower concentrations of greenhouse gasses (and emissions).

While there is no consensus on the probabilities associated with the emissions scenarios, the range of outcomes infer possible futures of interest to those compiling the scenarios. However, views of possible futures will evolve over time. For the design guidance in this manual, it is not prudent to design for the most pessimistic scenario, or for the most optimistic scenario.

Therefore, FHWA recommends use of a middle to above-middle emissions scenario from the latest set of scenarios for design. The most current set are the RCP scenarios and RCP 6.0 represents the middle to above-middle emissions scenario.

Furthermore, FHWA recommends analyses of additional scenarios so that the design team is informed about a range of possible outcomes. How the design team uses the information depends on the service life and criticality of the asset. In the same way that Table 7.5 links confidence intervals with plan/project characteristics, the design team should consider a broader range of scenarios in formulating the plan or design. For critical assets or assets with an expected service life greater than 30 years, FHWA recommends broadening the range by considering both the RCP 6.0 and RCP 8.5 scenarios. Also, given that the emission trajectories have been close to the high end of the scenario range, and GHGs are persistent in the atmosphere, FHWA views the two lower scenarios (RCPs 4.5 and 2.6) as less likely until emission rates decline sufficiently to suggest future concentrations in line with the lower scenarios.

FHWA recommends considering projections from the full range of GCM model output (one for each model) included on the DCHP website for each scenario considered. The DCHP includes data for 21 models, including 12 that have used emission scenario RCP 6.0. As recommended in the CMIP User's Guide, data from all 12 models should be downloaded. Because each model represents a physics-based representation of climate, it is reasonable to consider the outputs of each to be equally likely. By downloading multiple models, the designer can derive confidence limits based on the statistics of these data.

7.4. Levels of Analysis

This section describes the alternative levels of analysis. As methods and data improve, the types of approaches may change, but the general framework is robust because of its reliance on the use of confidence limits.

FHWA has developed a general process for transportation facility adaptation assessments (FHWA 2013). This process provides an 11-step framework for determining the vulnerabilities of an individual transportation facility to climate change, developing adaptation options to mitigate risks of anticipated changes, and selecting a course of action. The 11 steps are:

1. describe the site context,
2. describe the existing / proposed facility,
3. identify climate stressors that may impact infrastructure components,
4. decide on climate scenarios and determine the magnitude of changes,
5. assess performance of the existing / proposed facility,
6. identify adaptation option(s),
7. assess performance of the adaptation option(s),
8. conduct an economic analysis,
9. evaluate additional decision-making considerations,
10. select a course of action, and
11. plan and conduct ongoing activities.

The guidance is this chapter focuses on activities that would generally occur as part of steps 4 through 7 of the overall process.

7.4.1. Level 1 – Historical Discharges

The level 1 analysis is fundamentally based on the application of standard hydrologic design techniques for estimating a design discharge based on historical climate and watershed data. In addition, a level 1 analysis includes a qualitative assessment of future conditions and a determination of the significance of those conditions for the plan or project. A level 1 analysis might be appropriate for projects with low failure risks and/or a shorter hydrologic service life.

As noted in Table 7.1, the planner designer might use the rational, NRCS graphical peak, unit hydrograph, continuous simulation, gaged data, regional regression, or any other hydrologic tools appropriate for the situation. As with any hydrologic analysis, the design team should obtain the necessary historical data required as inputs to the selected models to generate the design discharges.

The future assessment in level 1 is qualitative and primarily based on programmatic tools and data prepared by state, regional, or local organizations that might have addressed projected discharge trends and guidance pertinent to the project location. These programmatic tools and data might address climate change, LULC, or other factors.

As also noted in Table 7.1, level 1 analyses include a qualitative resilience assessment of the plan or project. If, for example, the qualitative assessment of future discharges suggests increasing discharges over the lifetime of the project, then the design team should conduct sensitivity analyses with higher discharges to explore the potential consequences of that possible outcome. Evaluating discharges higher than the design discharge does not change the design team's responsibility to satisfy applicable design criteria at the design discharge, but it does provide additional information regarding the exposure consequences of larger events. A level 1, resilience assessment could be as simple as evaluating the costs and benefits of increasing the size of a culvert by one standard size over that required by the minimum design criteria.

Conversely, if the qualitative assessment of future discharges suggests decreasing discharges over the lifetime of the project, then the design team should use the discharges based on historical data. The project must serve its function in the short term as well as the long term and lowering design discharges based on future projections would jeopardize performance in the near term. FHWA anticipates a majority of projects will be appropriately considered with a level 1 analysis.

7.4.2. Level 2 – Historical Discharges/Confidence Limits

For level 2, the designer/planner explicitly considers the data uncertainty present in the historical record and uses that information to identify an appropriate range of conditions — based on the confidence limits — over which to evaluate the resilience of the proposed plan or project. Depending on the appropriate hydrologic design method for the situation, these confidence limits may apply to precipitation, land use, or flow data. The design team should consider model uncertainty where such information is available.

The future assessment in level 2 is quantitative rather than qualitative as was described for level 1. Like level 1, the assessment should use any programmatic tools and data prepared by state, regional, or local organizations that might have addressed projected discharge trends and guidance pertinent to the project location.

For a level 2 analysis, the design team should perform a trend analysis on historical precipitation data if using rainfall/runoff models and on historical discharge data if using the LPIII statistical model. Trend tests discussed previously in this manual (Section 4.3.1) can be used to make a quantitative assessment. For most applications with gaged flow sites, the Mann-Kendall test for gradual changes and the Pettitt test for abrupt changes are appropriate. For gradual changes, the period of record analyzed is critical. Except in rare cases, record length should not be less than 30 years and ideally should be longer, if possible, to avoid detection of trends that are actually part of natural cyclical variations. Unless other guidance is available, a significance level of 5 percent is appropriate for these tests. Similar analyses can be conducted with precipitation data, though NOAA Atlas 14 has already performed and reported these results. NOAA Atlas 14 should be consulted for trends in historical precipitation data.

The level 2 analyses also include a quantitative resilience assessment of the plan or project using the discharges generated based on the computed confidence limits. The design team should evaluate the performance of the project using the high and low confidence limits to examine and, when appropriate, mitigate undesirable outcomes. The design should comply with applicable design criteria related to the standard design discharge, but the design team should evaluate the consequences of larger and smaller discharges. For example, when considering a culvert size for a site, the size selected should be based on the design discharge in accordance with applicable design criteria. However, alternative sizes should be evaluated over the range of flows. The final selection should consider the full range of performance, as well as other considerations such as cost and likely repair and maintenance expenses over the life of the project.

As with level 1 analyses, if the assessment of future discharges suggests decreasing discharges over the lifetime of the project, then the design team should use the discharges based on historical data. The project should serve its function in the short term as well as the long term and lowering design discharges based on future projections would jeopardize performance in the near term.

As noted in Table 7.1, the design team might use the rational, NRCS graphical peak, unit hydrograph, continuous simulation, gaged data, regional regression, or any other hydrologic tools appropriate for the situation. The following sections describe specific guidance for application of rainfall/runoff and statistical models including the development of confidence limits.

Designers may develop confidence limits on the discharge based on probability distributions for the model input variables, the model itself, or some combination of these. To a large degree, the method chosen will determine the approach needed to estimate the confidence limits. However, in all cases, FHWA recommends the guidance in table 7.5 for selecting the appropriate confidence limits. For a level 2 analysis, the focus is on estimating confidence limits for historical conditions.

7.4.2.1. Rainfall/Runoff Models

For rainfall/runoff models, such as the rational method, NRCS graphical peak method, or a unit hydrograph, designers can estimate confidence limits on discharge from information about the input variables. The models themselves generally do not include any intrinsic uncertainty information.

While the complexity of rainfall/runoff models varies widely, as does the number of input parameters, all rainfall/runoff models require at least four inputs: 1) drainage area, 2) precipitation, 3) time of concentration (or other time parameter), and 4) land use. The manner in which the models represent these parameters spatially and temporally may also vary greatly among models, making it difficult to generalize assessments for developing confidence limits.

To illustrate the concepts involved in estimating confidence limits, the NRCS unit hydrograph method is selected for detailed discussion because of its broad use and the general familiarity of it within the hydrologic design community. Ideally, the design team would determine the best estimate of each of the input variables – drainage area, precipitation depth, time of concentration, and LULC – and the probability distribution of the actual value for each of those variables. In traditional design, designers generally use the best estimates to generate a best estimate of the design discharge.

For drainage area, time of concentration, and LULC, different designers using different tools might each estimate different values. These differences and the frequency with which they might occur represent a probability distribution for each variable. While there is judgement involved in the determination of all parameters, the computation of drainage area and time of concentration are generally more objective and, therefore, more consistent. This consistency implies a much narrower probability distribution for the actual watershed characteristic values.

Curve number represents land use and soil type, which requires some subjectivity to estimate. A higher curve number represents higher runoff while a lower curve number represents lower runoff. Existing land use conditions and soil types can be reasonably estimated by inspection of current mapping, soil surveys, and field validation. However, there is variability based on the experience of the hydrologic engineer, the degree of disaggregation of the data, and the interpretation of that data. Generally, designers address this by making their “best” estimate of curve number(s) considering the resources available and the importance of the project. Designers may also conduct sensitivity analyses to explore the variability in the estimated design flow in response to changes in the curve number(s). However, sensitivity analyses rarely have associated probabilities that may be converted to confidence limits. Therefore, the probability distribution for the land use estimate is generally unknown.

The last of the four primary variables of the NRCS unit hydrograph method is precipitation, specifically, the 24-hour rainfall depth that corresponds to the return period of the design flow requirement. There are many sources for this information. FHWA considers the NOAA Atlas 14 to be the best available data source. Atlas 14 provides estimates for the 24-hour depth – and many other durations – over a range of return periods. Figure 7.1 shows an example graphical output from Atlas 14 for a location near Denver, Colorado.

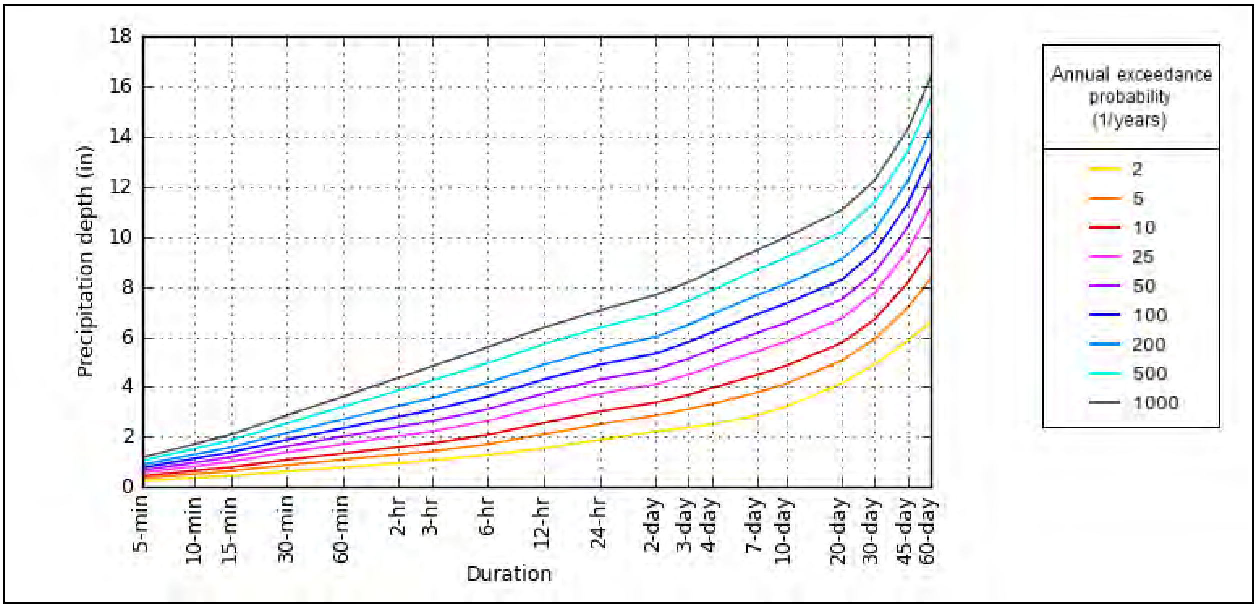

Figure 7.1. Depth-duration-frequency curve from NOAA Atlas 14.

Because of the statistical nature of the analyses supporting Atlas 14, confidence limits for the precipitation estimates are available. Figure 7.2 illustrates a representative graphical output for the 90 percent confidence interval for the 24-hour duration for the same location near Denver.

Atlas 14 also provides the data in tabular form as shown in Figure 7.3. For example, the 24-hour 100-year precipitation depth is 4.88 inches and the 90 percent confidence limits are 3.62 and 6.5 inches. Other confidence intervals can be computed from the 90 percent confidence interval.

One approach to establishing confidence limits for the estimated discharge is to perform Monte Carlo simulations based on variations in each of the input variables from known or assumed probability distributions. Where reasonable estimates of the probability distributions of the input variables are available and the effort is justified, Monte Carlo simulations are a sound approach to establishing confidence limits.

However, in many rainfall/runoff modeling situations, the only input variable for which a probability distribution is available is the precipitation. In this situation, another approach for estimating the confidence limits for discharge is to apply the confidence interval for precipitation that corresponds to the desired confidence interval for the precipitation along with the "best" estimates for the other input variables. This approach provides a reproducible basis for computing upper and lower confidence limit discharges. Because the other sources of uncertainty are not (and often cannot) be quantified, the confidence limits estimated for the discharge may be an underestimate or an overestimate depending on the sensitivity of the discharge to precipitation. However, the approach of estimating confidence limits, even if only based on precipitation uncertainty, is superior to implementing plans and designs based on only a single design flow.

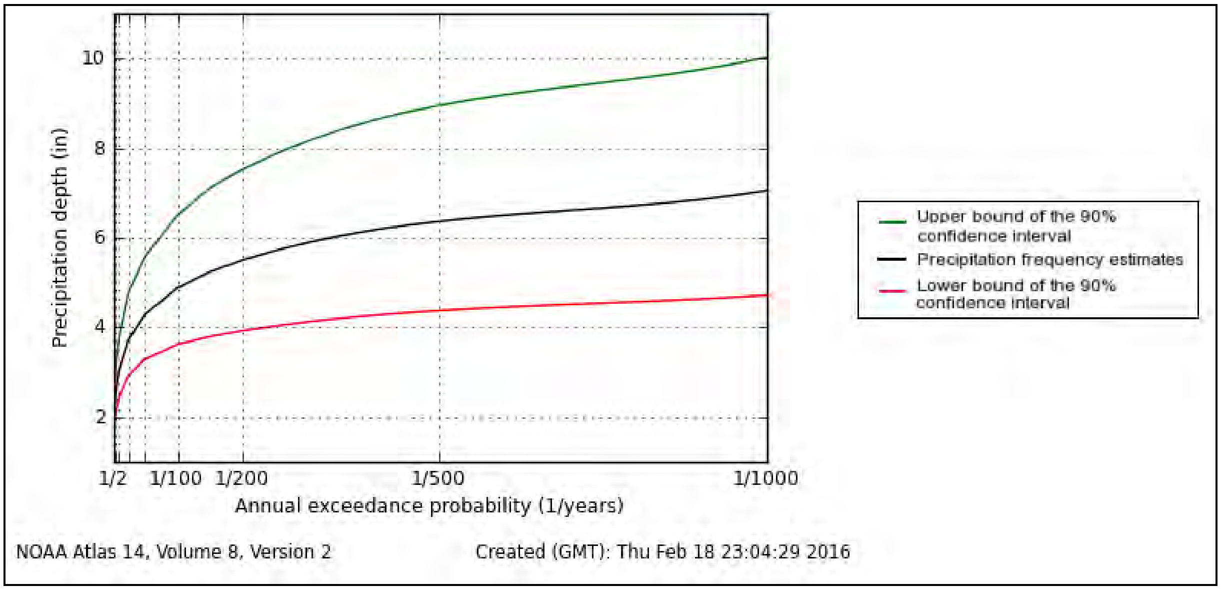

Figure 7.2. 24-hour precipitation with confidence limits from NOAA Atlas 14.

AMS-based precipitation frequency estimates with 90% confidence intervals (in inches)[1]									
Duration	Annual exceedance probability (1/years)								
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
24-hr	1.88 (1.53-2.31)	2.51 (2.04-3.08)	3.01 (2.43-3.72)	3.72 (2.92-4.78)	4.29 (3.29-5.58)	4.88 (3.62-6.50)	5.50 (3.93-7.53)	6.37 (4.38-8.95)	7.05 (4.71-10.0)

Figure 7.3. Tabular output from NOAA Atlas 14.

The general steps to estimate confidence limits with the NRCS unit hydrograph procedure are:

1. estimate the design discharge using the best estimates of the input variables,
2. estimate the probability distributions for the input variables, where feasible,
3. compute the confidence limits using Monte Carlo simulation or the appropriate confidence limits of the input variables, and
4. assess/design the plan/project considering the full range of discharge within the confidence limits.

Consider the design of a culvert with an anticipated hydrologic service life of 80 years, Table 7.5 recommends a confidence interval of 90 percent. If the best estimates of curve number, drainage area, and other inputs are developed, executing the rainfall/runoff model for the 90 percent confidence interval for precipitation will yield flows that can be used as the 90 percent confidence discharges. If probabilities can be assigned to other input parameters, these are used with the probabilities associated with precipitation to estimate the appropriate cumulative confidence limits for the discharge.

Once the design team estimates the design flow and upper and lower confidence limit flows, they evaluate the proposed plan/project for this range of flows that reflect, at least partially, historical uncertainty. Accounting for this uncertainty allows design of more resilient projects.

7.4.2.2. Statistical Models

If a statistical model, such as regional regression equations or Log-Pearson Type III (LPIII) analysis of gage data, is appropriate for the situation, model uncertainty data are available. The design team may use this information to create confidence limits.

Each regional regression equation has an associated parameter called percent standard error, which can be converted to confidence limits. The steps to accomplish this are:

1. estimate the design flow,
2. take the log (base 10) of the design flow,
3. convert standard error in percent to standard error in log (base 10) units,
4. compute the confidence limits in log units,
5. compute the confidence limits in flow units, and
6. assess/design the plan/project considering the range of flow within the confidence limits.

Developing confidence limits for LPIII analysis of gaged flow data is more complex and depends on the number of observations in the flow record. The details of this method are summarized in several references including HDS 2 and Bulletin 17B. Public domain software developed and maintained by the USGS – PeakFQ Version 7.1 – may also be used to compute confidence limits, as well as the flood frequency curve, using an updated set of procedures (Cohn *et al*. 2001). The following detailed descriptions of the analysis steps are directly applicable to the regional regression equations, but generally describe the goals of the process when using the LPIII procedure or other statistical methods.

Step 1. Estimate design flow.

The first step represents the standard practice the design team performs when not considering model uncertainty. For example, a regional regression equation for the 100-year flow may have the form shown below:

$$Q_T = aA^{b_1}S^{b_2} \tag{7.1}$$

where:

Q_T = estimated T-year peak discharge
A = watershed drainage area
S = watershed slope
a = regression coefficient constant
b_1, b_2 = regression exponent constants

The design team develops the appropriate values for watershed drainage area and slope and uses the equation, with the constants for the 100-year equation, to compute the 100-year flow. The design team would consider this the best – or most likely – estimate of the design flow.

Step 2. Compute log of the design flow.

In step 2, the design team converts the design flow to log units as shown below:

$$Y_T = log_{10}(Q_T) \tag{7.2}$$

where:

Y_T = estimated T-year peak discharge in log units
Q_T = estimated T-year peak discharge

Step 3. Compute standard error in log units.

For step 3, the design team converts the standard error – typically given in percent – to log (base 10) units using the following standard equation:

$$SE_{log10} = \left[\frac{1}{5.302} ln\left\{\left(\frac{SE_{\%}}{100}\right)^2 + 1\right\}\right]^{0.5} \tag{7.3}$$

where:

SE_{log10} = standard error in log (base 10) units
$SE_{\%}$ = standard error in percent

Step 4. Compute confidence limits in log units.

In step 4, the confidence limits are calculated in log units using the following equations:

$$Y_{T,U} = Y_T + K_c SE_{log10} \tag{7.4}$$

$$Y_{T,L} = Y_T - K_c SE_{log10} \tag{7.5}$$

where:

$Y_{T,U}$ = upper confidence limit in log units
$Y_{T,L}$ = lower confidence limit in log units
K_c = confidence limit coefficient corresponding to confidence interval *c*
SE_{log10} = standard error in log (base 10) units

The confidence limit coefficient is a function of the confidence interval as summarized in Table 7.6 and assumes the residuals in log units are distributed normally. A higher confidence interval implies a wider gap or interval between the lower and upper confidence limits and results in a higher confidence limit coefficient. Selection of the appropriate confidence limit may consider a variety of factors including the expected service life as described in Table 7.5.

Table 7.6. Confidence limit coefficient.

Confidence Interval	Lower Confidence Limit	Upper Confidence Limit	Confidence Limit Coefficient, K_c
38%	31%	69%	0.500
68%	16%	84%	1.000
90%	5%	95%	1.645

Step 5. Compute confidence limits in flow units.

In step 5, the design team converts the upper and lower confidence limits in log units back to discharge units as shown below:

$$Q_{T,U} = 10^{Y_{T,U}} \tag{7.6}$$

$$Q_{T,L} = 10^{Y_{T,L}} \tag{7.7}$$

where:

$Q_{T,U}$ = estimated upper confidence limit T-year peak flow in discharge units
$Q_{T,L}$ = estimated lower confidence limit T-year peak flow in discharge units
$Y_{T,U}$ = upper T-year confidence limit in log units
$Y_{T,L}$ = lower T-year confidence limit in log units

Step 6. Assess/design plan/project.

Step 1 reflects the standard design practices for estimating a design flow. Steps 2 through 5 result in two additional discharges that bracket the design flow reflecting uncertainty in the method and historical data. In this step 6, the design team evaluates the possible plans and projects not only on the design flow, but also at the higher and lower confidence limits flows.

Evaluation of the higher confidence limit flow does not imply that the project must accommodate that flow according the same criteria applicable to the design flow. Evaluation of the higher flow does not imply that the hydraulic opening(s) must be made larger. That is an option, but only one option. It does mean that the design team should identify and , where appropriate, mitigate the consequences of the higher flow on the project. For example, if the higher flow results in overtopping that would not occur under the design flow, the designer should evaluate the implications for failure of the embankment and explore cost-effective options for mitigating or preventing such damage.

Evaluation of the lower limit discharge provides an opportunity to consider consequences to the project if the design flow is an overestimate. For example, at the lower flow are sediment transport or stream stabilization issues apparent? As with the high confidence limit flow, assessment of the low confidence limit flow provides an opportunity to identify potential problems and incorporate cost-saving measures at the outset of a project.

By identifying and assessing consequences associated with the upper and lower confidence limit flows, in addition to satisfying pertinent criteria at the design flow, a more resilient plan or project may be implemented. Although, the range of flows are based on historical uncertainty, examining the project based on range of flows rather than a single flow should provide a more resilient project with respect to future conditions because more than a single design flow is evaluated.

7.4.3. Level 3 – Historical Discharges/Confidence Limits with Precipitation Projections

A level 3 analysis represents a transition between levels 1 and 2, which are primarily focused on historical data, and levels 4 and 5, which quantitatively incorporate projections of future climate into project evaluation. Level 3 is essentially a decision point for the design team to determine if a level 4 or 5 analysis is justified for the plan or project.

Example Computation of Confidence Limits for Regression Equations

A project requires the development of a 25-year design flow and associated confidence limits for historical data. The applicable regional regression equation is:

$$Q_{25} = 180A^{0.776}S^{0.554}$$

The required input data for the watershed was estimated to be the drainage area, A, at 10 mi^2 and the watershed slope, S, at 26 ft/mi. The standard error of the equation was reported to be 40 percent.

The anticipated design life is anticipated to be 50 years. Therefore, the recommended confidence interval is 68 percent.

Step 1. Estimate design flow.

$Q_{25} = 180(10)^{0.776}(26)^{0.554} = 6{,}534\ ft^3/s$ *(reported as 6,500)*

Step 2. Compute log of the design flow.

$$Y_T = log_{10}(Q_T) = log_{10}(6534) = 3.815$$

Step 3. Compute standard error in log units.

$$SE_{log10} = \left[\frac{1}{5.302} ln\left\{\left(\frac{SE_{\%}}{100}\right)^2 + 1\right\}\right]^{0.5} = \left[\frac{1}{5.302} ln\left\{\left(\frac{40}{100}\right)^2 + 1\right\}\right]^{0.5} = 0.167$$

Step 4. Compute confidence limits in log units.

For the confidence interval of 68 percent, Kc = 1.00.

$$Y_{T,U} = Y_T + K_c SE_{log10} = 3.185 + 1.00(0.167) = 3.982$$

$$Y_{T,L} = Y_T - K_c SE_{log10} = 3.185 - 1.00(0.167) = 3.648$$

Step 5. Compute confidence limits in flow units.

$Q_{T,U} = 10^{Y_{T,U}} = 10^{3.982} = 9{,}594\ ft^s/s$ *(reported as 9,600)*

$Q_{T,L} = 10^{Y_{T,L}} = 10^{3.648} = 4{,}446\ ft^s/s$ *(reported as 4,400)*

Step 6. Assess/design plan/project.

The design flow is 6,500 ft^3/s. The project should be evaluated for flows ranging from 4,400 ft^3/s to 9,600 ft^3/s to consider performance and potential mitigation/adaptation strategies.

The added element of a level 3 analysis over a level 2 analysis is the retrieval of projected 24-hour precipitation and comparison of projected precipitation with historical precipitation. The level 3 analysis introduces a new concept called the climate change indicator (CCI). The CCI provides a measure of the projected change in precipitation from historical conditions relative to the uncertainty within the estimates of historical rainfall. This indicator provides important information for the design team to consider when determining if a level 4 or higher analysis is appropriate.

FHWA does not recommend using arbitrary increases in flows, for example a 10 percent increase, to estimate projected discharges from historical discharges. Rather, FHWA recommends using the CCI, and other information, to determine if a level 4 analysis, based on sound hydrologic methodologies and data, is justified.

7.4.3.1. Projected Change in T-year 24-hour Precipitation

The objective is to estimate the projected change in the T-year 24-hour precipitation value as an indicator of the potential for climate change (climate nonstationarity) to affect the estimated design discharge based on historical data. With this indicator, the design team should evaluate whether more detailed analysis, that is, a level 4 analysis, of climate projections is appropriate. Regardless of whether the design team is using rainfall/runoff or statistical models for the hydrologic analysis, this indicator is useful for evaluating the potential for changes in flood flows resulting from projected changes in climate for the T-year event.

As described in Section 7.3, FHWA recommends the use of multiple climate models. At a minimum, the design team should develop a climate change indicator for RCP 6.0 and FHWA recommends investigation of other emissions scenarios when possible as summarized in Section 7.3.

The development of this indicator begins by acquiring the downscaled daily precipitation data from the DCHP website, or equivalent database. The design team should download all years of available data (1950 through 2099) so that if there are changes in the periods of interest, all available data are present.

Once the daily data are downloaded, the indicator is developed by processing the data according to the following steps. If more than one emission scenario is examined, these steps are repeated for each scenario:

1. average the observed daily precipitation data across all cells,
2. determine the maximum annual value for each year,
3. select the baseline and future periods,
4. compute the baseline and future T-year 24-hour precipitation for each model,
5. estimate the projected T-year 24-hour precipitation for each model,
6. compute the mean for the projected T-year 24-hour precipitation, and
7. evaluate the need for additional analysis.

Step 1. Average the modeled daily precipitation data across all cells.

The design team should download a minimum of four cells for small watersheds and more if needed to spatially cover larger watersheds. The modeled daily precipitation data should be averaged across all cells to create a single daily precipitation time series for each GCM. Averaging these data assumes that the design team is using a watershed-averaged model. If the model is spatially disaggregated, the averaging should be at the level needed to support the hydrologic model, not over the entire watershed. This step is completed for each climate model.

Step 2. Determine the maximum annual value for each year.

An annual maxima series (AMS) includes the largest value in each year. FHWA recommends the use of the water year because this is standard procedure for historical data, but use of the calendar year is acceptable for developing projections. The US DOT CMIP Climate Data Processing Tool performs this function, but any tool may be used. If the Tool is used, FHWA recommends that the AMS data be copied to a separate spreadsheet for further analysis because the Tool contains a large volume of data not needed for this analysis that will slow down subsequent computations. The result of this step is an AMS for each climate model.

Step 3. Select the baseline and future periods.

Data are available from 1950 through 2099. The design team should select a period for the baseline (historical) analysis and a future period so that the difference between the two can be calculated. Neither period should be less than 30 years and at least 50 years is preferable. However, the selection should be made based on the needs of the project.

Definition of the baseline period depends on the observed historical data that are available. For example, if NOAA Atlas 14 is appropriate to define the T-year 24-hour precipitation for the project, then that sets the baseline. However, because the modeled data only extend back to 1950, this year represents the earliest baseline year.

Definition of the future period depends on the current year and the anticipated service life of the project. FHWA recommends use of data from the current year through the end of the modeled data set (2099) unless there are compelling reasons to use a shorter period. For example, if the service life is expected to be short with little chance for its extension, a shorter period might be appropriate.

Several studies, for example FHWA (2013), have explicitly evaluated multiple future sub-periods. Multiple sub-periods provide the opportunity to identify periods in the projections where the severity of extreme precipitation may be decreasing as well as increasing. However, there is also a risk that the sub-periods will be sufficiently short that they merely capture natural wet and dry periods that have been observed in the historic record rather than long-term nonstationary behavior. Further investigation of the validity of considering sub-periods for design purposes is a recommended future research effort.

Step 4. Compute the baseline and future T-year 24-hour precipitation for each model.

The T-year return period is computed for each model AMS for both the baseline and future periods. This is accomplished by fitting the AMS to an appropriate probability distribution. In the preparation of Atlas 14, NOAA evaluated several distributions for their fit to precipitation data. In most parts of the U.S. NOAA selected the GEV distribution for analyzing 24-hour duration data. While there is no certainty that historical distributions will remain the same in the future, there is also no information available to the contrary. The analyst should consult NOAA Atlas 14 for the proper distribution to use. The results of this step are modeled baseline and future T-year 24-hour precipitation estimates for each climate model.

Step 5. Estimate the projected T-year 24-hour precipitation for each model.

The projected T-year 24-hour precipitation is estimated by computing the difference between the future and baseline T-year 24-hour precipitation values for each model from the previous step and adding that difference to the observed T-year 24-hour precipitation. The design team would use the observed T-year 24-hour precipitation from NOAA Atlas 14 or other source appropriate for the project. From this step, a projected T-year 24-hour precipitation from each climate model is estimated.

Step 6. Compute the mean for the projected T-year 24-hour precipitation.

The design team computes the mean assuming that each climate model outcome is equally likely.

Step 7. Evaluate the need for additional analyses.

The climate change indicator is a measure of how much the mean value of the T-year 24-hour precipitation is changing from observed to projected conditions relative to the observed uncertainty in the observed (historical) data as shown in the following equation:

$$CCI = \frac{P_{24,T,P} - P_{24,T,O}}{P_{24,T,O,U} - P_{24,T,O}} \tag{7.8}$$

where:

CCI = Climate change indicator
$P_{24,T,P}$ = Projected T-year 24-hour precipitation
$P_{24,,T,O}$ = Observed T-year 24-hour precipitation
$P_{24,T,O,U}$= Upper 90% confidence limit T-year 24-hour precipitation for the observed data

The projected T-year 24-hour precipitation is taken as the mean value computed in step 6. For the purpose of computing this indicator, the design team can take the observed T-year 24-hour precipitation and the corresponding upper 90 percent confidence limit from NOAA Atlas 14. The 90 percent confidence limit is chosen because this value is provided by Atlas 14. These values should be selected based on the annual series rather than partial duration series, both of which are available in Atlas 14.

Figure 7.4 describes the CCI conceptually. The observed T-year 24-hour precipitation is actually the mean (most probable) value estimated from the historic data. There is a probability that the actual value is less or more is indicated by the probability curve shown in the figure. The upper 90 percent confidence limit of the T-year 24-hour precipitation is also shown. The difference between these two values is represented as B. The projected T-year 24-hour precipitation is indicated in the figure as being larger than the historical value. The difference between these two values is represented as A. The CCI is simply the ratio of A to B.

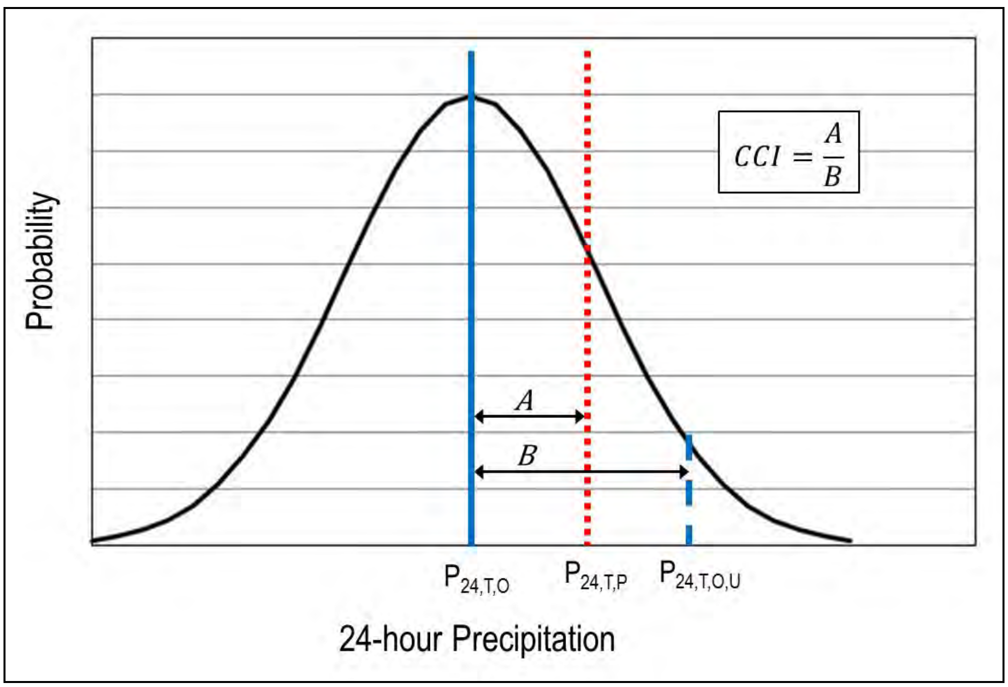

Figure 7.4. Definition of the CCI.

Changes in the T-year 24-hour precipitation do not necessarily translate to proportional changes in the T-year design discharge. However, the indicator provides a measure of how much change in precipitation the designer might expect relative to uncertainty in the observed data. If this indicator is large, then the climate change effects on flow might be large and if this indicator is small, the effects on flow might be small.

The purpose of the indicator is to inform a decision by the project team whether to perform more detailed analyses of projected conditions as is called for in a level 4 analysis or whether the use of the historical confidence limits in the level 2 analysis and this subsequent level 3 analysis is sufficient for moving forward with evaluation of the plan or project.

Since the needs and characteristics of each project are unique, the decision about moving to level 4 rests with the design team. However, as a broad guideline, climate change indicator values of less than 0.4 suggests that evaluating a project based on the historical confidence limits in level 2 will provide a reasonable basis for evaluating project performance. Conversely, a climate change indicator greater than 0.8 suggests further analysis of projected conditions might be appropriate. For situations between these values, the project specifics should be carefully weighed by the design team to determine whether a level 4 analysis is advisable. Because the CCI approach is new, FHWA recognizes that guidance regarding its use may evolve as experience with it is gained.

7.4.3.2. Additional Evaluation

As with level 2 analyses, if the qualitative assessment of future discharges suggests decreasing discharges over the lifetime of the project, then the design team should use the discharges based on historical data. The project should serve its function in the short term as well as the long term and lowering design discharges based on future projections would jeopardize performance in the near term.

FHWA discourages the use of arbitrary increases in discharge to account for changes in climate. If projected discharges based on climate changes are required, FHWA recommends a level 4 analysis.

7.4.4. Level 4 – Projected Discharges/Confidence Limits

For level 4, the design team seeks to develop projected discharges and confidence limits explicitly incorporating future projections of one or more key variables. A level 4 analysis builds on the work described in lower levels with projections of climate and land use along with the data uncertainty associated with those projections. Where a basis exists, other projected variables may also be incorporated into a level 4 analysis.

Climate data are drawn from downscaled climate projections using the recommended data sources and emissions scenarios as discussed in Section 7.3. Level 4 climate projections should also consider temperature data in those areas that experience precipitation in the form of rain and snow. In the preparation of its Atlas 14 series of reports, NOAA explicitly considered this distinction in areas where both types of precipitation are possible. (See volume 8, for example.) For future conditions, where both temperature and precipitation changes are projected to occur, the fraction of precipitation falling as rainfall may shift from the relation that exists today. For regions of the U.S. where this is possible, the design team should examine the temperature and precipitation changes before treating precipitation projections as rainfall projections.

When feasible, the design team should also consider land use projections. Projections of land use are frequently available from local and regional planning agencies and are often presented as a series of scenarios and/or ranges. One national source of future land use scenarios is a database of impervious area projections (EPA 2009). However, probabilities are not generally assigned to these land use scenarios because they are predicated on human behavior and policy decisions that cannot generally be predicted with any certainty, especially over longer time horizons.

With a level 4 analysis, high and low confidence limits are developed and evaluated for plan/project performance based on the projections of future variables. The design team should consider both historical and projected confidence limits for developing a resilient plan/project. The following sections discuss specific guidance for development of projected discharges and confidence limits based on the type of hydrologic modeling.

7.4.4.1. Rainfall/Runoff Models

Recall that in the discussion of level 2 analyses, this manual noted that the complexity of rainfall/runoff models varies widely, as does the number of input parameters required. However, it was also noted that all rainfall/runoff models require at least four inputs: 1) drainage area, 2) precipitation, 3) time of concentration (or other time parameter), and 4) land use. Therefore, these models can be used to project future design flows and confidence limits to the extent that planners/designers can make projections of one or more of these variables.

The ability to make projections of these variables, with associated probabilities is currently limited. The following sections provide guidance on the development of projected climate data, particularly precipitation.

7.4.4.1.1 Estimating the T-year 24-hour Precipitation

For some rainfall/runoff models, such as the NRCS graphical peak discharge and the NRCS unit hydrograph methods, a T-year 24-hour duration rainfall depth is a required input. The objective of this section is to describe how to process historical and projected daily precipitation data from downscaled climate models to a series of annual maxima. These series are then analyzed to estimate the 24-hour precipitation for a given return period along with the associated confidence limits appropriate for the project.

As part of the level 3 analyses, Section 7.4.3.1 provided a description for estimating an indicator of the change in T-year 24-hour precipitation. For this level 4 analysis, the design team expands the detail of level 3 analysis to produce projected precipitation values and confidence limits for incorporation into the hydrologic model.

In Section 7.4.3.1, the first six steps describe the process for computing a projected T-year 24-hour precipitation value. They are repeated here, as follows:

1. average the observed daily precipitation data across all cells,
2. determine the maximum annual value for each year,
    a. estimate the point estimate correction,
    b. estimate the unconstrained 24-hour correction,
    c. adjust the model annual series data by the correction values,
3. select the baseline and future periods,
4. compute the baseline and future T-year 24-hour precipitation for each model,
5. estimate the projected T-year 24-hour precipitation for each model, and
6. compute the mean ***and confidence interval*** for the projected T-year 24-hour precipitation.

This list includes two additions to the process discussed previously. The first pertains to step 2 where three substeps are added convert the data to be consistent with observed data such as that provided by NOAA Atlas 14. The second addition is to include the computation of the confidence interval for the projected T-year 24-hour precipitation in addition to the mean in step 6. These following sections explain these additions.

Step 2a. Estimate the point estimate correction.

Steps 2a through 2c provide an adjusted AMS by means of two corrections such that the modeled AMS represents the same quantity as an observed AMS. In this step, a correction to convert the modeled quantity to a point estimate is calculated. The downloaded climate model data represent average precipitation over an area of the approximately 56 square mile cell size. However, hydrologic modeling tools generally require point estimates, which are, in turn, adjusted to the area of the watershed. The point/area conversion for the 24-hour duration precipitation and a 56 square mile watershed is 1.04 (reference HDS 2 and TP40). If a different downloaded data source with an area smaller than 56 square miles is used, the point/area conversion would be adjusted accordingly.

Step 2b. Estimate the unconstrained 24-hour correction.

The second correction is required because the downscaled data reflect 24-hour data constrained by the clock, that is, from midnight to midnight. However, hydrologic modeling tools require unconstrained 24-hour periods that may, for example, extend from 3 pm one day to 3 pm the next. The unconstrained 24-hour precipitation depth will be greater than or equal to the constrained daily precipitation depth. NOAA Atlas 14 employs these corrections. The corrections vary around the country, but generally approximate 1.13.

Step 2c. Adjust the model annual series data by the correction values.

In this step, the design team adjusts the AMS with the corrections from steps 2a and 2b as follows to create a corrected AMS:

$$P_{24,i} = f_{p/a} f_{u/c} P_{24,i,u} \tag{7.9}$$

where:

$P_{24,i}$ = corrected annual maximum 24-hour precipitation for year i
$P_{24,,I,u}$ = uncorrected annual maximum 24-hour precipitation for year i
$f_{p/a}$ = correction factor to point data
$f_{u/c}$ = correction factor to unconstrained data

The result of this step is a corrected AMS for each climate model.

Step 6. Compute the mean and confidence interval for the projected T-year 24-hour precipitation.

The design team computes the mean and confidence interval assuming that each climate model outcome is equally likely. First, the mean and standard deviation of the data are calculated. Next, the appropriate confidence interval for the project based on Table 7.5, or project-specific considerations, is chosen. Then, the corresponding confidence limit coefficients (K-value) from Table 7.6 are determined. Finally, the upper and lower confidence limits are computed from the following equations:

$$P_{24,T,U} = \bar{P}_{24,T} + K_c SD \tag{7.10}$$

$$P_{24,T,L} = \bar{P}_{24,T} - K_c SD \tag{7.11}$$

where:

$P_{24,T,U}$ = upper confidence limit for the T-year 24-hour precipitation
$P_{24,T,L}$ = lower confidence limit for the T-year 24-hour precipitation
$\bar{P}_{24,T}$ = mean T-year 24-hour precipitation estimate
K_c = confidence limit coefficient corresponding to confidence interval *c*
SD = standard deviation of the T-year 24-hour precipitation estimates

The design team should compare the projected T-year 24-hour precipitation values and confidence limits with the observed T-year 24-hour precipitation values and confidence limits from NOAA Atlas 14 or other source generated from the level 2 analyses. Although the Atlas 14 confidence limits and the projected confidence limits are computed using different procedures because the available types of data are different, the comparison will provide insight into the nonstationarity of precipitation at the project site. The design team applies the projected mean value and confidence limits to the hydrologic model for additional insight into potential future discharge conditions.

7.4.4.1.2 T-year Precipitation with Durations Less than 24 Hours

Some rainfall/runoff models require precipitation inputs with durations less than 24-hours. The previous section focused on generation of 24-hour duration precipitation estimates (mean and confidence limits) for the T-year event because daily data are available from the DCHP. Estimates for shorter durations, down to the 1-hour duration, may be obtained by determining the historical ratio of the X-hour duration to the 24-hour duration from the data in NOAA Atlas 14 for the site and applying that ratio to the projected 24-hour duration values. While these ratios may change over time, this is a reasonable estimate in the absence of other alternatives and represents best available data.

7.4.4.2. Statistical Models

The use of statistical models for explicitly incorporating projected land use and climate changes is frequently limited because there is no means for effectively incorporating the projected changes. For example, a statistical analysis of historical gaged flows (Log-Pearson III) can be a good method for a level 2 analysis because tools are available to estimate design discharge, compute confidence limits, and analyze trends. However, there is currently no accepted method for projecting future annual maximum flows based on changes in land use and climate.

Many regional regression equations also do not have potential for use in a level 4 analysis because they do not have a mechanism for incorporating future conditions. However, in limited areas of the country there are regional regression equations with potential for application in a level 4 analysis. Regression equations are periodically updated, which may lead to an increase in the availability of useful equations.

An example regression equation that might allow estimation of future conditions based on projected changes in mean annual precipitation in the future is shown below:

$$Q_T = aA^{b_1}P^{b_2} \tag{7.12}$$

where:

Q_T = estimated T-year peak discharge
A = watershed drainage area
P = mean annual precipitation
a = regression coefficient constant
b_1, b_2 = regression exponent constants

This equation was developed based on historical data, as are all regional regression equations. It was based on a particular range of values for watershed area and mean annual precipitation that the equation developers determined to be significant for estimating peak discharge for the historical period.

Use of any regional regression equation outside of the bounds within which it was developed should be carefully considered both in terms of the nature of the extrapolation and the alternative tools that might be available to the design team to incorporate climate change. With respect to the first consideration, regional regression equations are intended to be applied to ungaged watersheds and are, therefore, at some level, extrapolated beyond the set of watersheds that are gaged. If, as in the example above, the watershed drainage area and mean annual precipitation of the ungaged watershed are within (or close to) the range of values from the gaged watersheds used to develop the equation, then that extrapolation is considered reasonable and the equation may be used to estimate a peak discharge. Similarly, if a projected mean annual precipitation derived from climate modeling data is within the range of values used to develop the regression equation, this too, may be a viable extrapolation.

In addition, the conditions to which the equations are applied should be representative of the conditions from which the underlying data were collected. Under nonstationary conditions, the future is different from the past possibly leading to the conclusion that regional regression equations should not be used for future projections. However, one should also not assume that all hydrologic relationships are restructured under nonstationary conditions and that no utility exists in regional regression equations for future projections. They can be useful engineering tools for planning, analysis and design purposes

This leads to the second factor in evaluating whether extrapolation of regional regression equations for future climate conditions represents an appropriate tool: what are the alternatives? An uncalibrated rainfall/runoff model with no measures of model uncertainty may not be a better alternative. Because this manual is to provide guidance on the use of various tools, but leave the ultimate selection of the tools to the design team, use of regional regression equations, when they include appropriate independent variables, should not be ruled out as long as the values of those variables fall within the acceptable range as dictated in current practice.

For those situations where the design team determines that regional regression equations are an appropriate tool for projecting future conditions, the following sections briefly discuss approaches for incorporating climate, specifically changes in mean annual precipitation, and land use projections.

7.4.4.2.1 Projections of Mean Annual Precipitation

For some applications, such as for the equation described in the previous section, mean annual precipitation (MAP) may be required. The design team may extract MAP using the US DOT CMIP Climate Processing Tool. Currently, the DCHP provides projections through 2100. While there may be reasons to truncate this projection horizon, such as a relatively short anticipated service life, the full projection period should be used in most cases to compute the MAP for each climate model/scenario. Projected MAP should be calculated as the difference between the modeled future and modeled baseline MAP added to the observed MAP for each model.

To compute the confidence limits, the designer uses the MAP from each model to compute a mean and standard deviation over all the models. Then, based on the confidence interval desired, the designer performs the computations analogous to those in Equations 7.10 and 7.11 to compute the confidence limits associated with the mean MAP across all models.

7.4.4.2.2 Land Use Land Cover Projections

Incorporating Land Use Land Cover (LULC) projections into regional regression equations is challenging because most current equations from the USGS do not include an independent variable, such as percent imperviousness, that can be used as a measure of LULC. However, as urbanization is increasing, more equations are being developed with such variables. For situations where such equations exist, they may represent a viable tool for situations described earlier with respect to climate changes.

For those regions where a LULC variable is not included in the equation, USGS developed a concept called the basin development factor (BDF). Although, USGS and other may develop new methods to replace the BDF, it is currently described as a viable technique in many documents including FHWA's HDS 2.

7.4.5. Level 5 – Projected Discharges/Confidence Limits with Expanded Evaluation

Level 4 uses generally available tools and projections of climate and land use. At level 5, the design team has determined that expanded expertise in hydrologic modeling, climate science, and/or land use planning is needed and secures custom site-specific projections.

The level 5 processes are fundamentally analogous to level 4 processes. The planner/designer should choose the most appropriate models and tools for the situation. At this level, more advanced hydrologic models might be justified. The design team will also chose the appropriate target confidence limits. The rationale for moving to a level 5 analysis might include response to one or more of the following needs:

- the importance or costs of a plan or project justify a higher level of analysis,
- additional insight into the appropriate emission or emission scenarios,
- identification of a smaller subset of GCMs that may be more appropriate for a given location,
- exploration of alternative downscaling strategies other than that available at the DCHP website,
- customized land use projections, and
- customized or experimental modeling tools.

Regardless of the data or tools used, the objective remains the same: produce a range of conditions over which the design team can evaluate the resilience of the plan or project.

7.5. Gaps in Existing Knowledge

The processes and data described in this chapter represent the ***best actionable engineering and science methods and data*** for the purposes of developing hydrologic estimates for planning and design. However, there are several areas where existing knowledge and methods could be improved including, but not limited to:

- assigning probabilities to emissions scenarios,
- techniques for estimating joint probabilities of model and data uncertainty,
- techniques for estimating model error for rainfall/runoff models,

- projections of annual maxima series of precipitation data for durations less than 24 hours,
- assessment of the ability of downscaled GCM data to produce annual maxima series of precipitation data at the 24-hour duration with the corresponding change in variability (standard deviation and skew),
- factors shifting precipitation from rain to snow or vice versa,
- considering future sub-periods versus a continuous period for projected precipitation,
- improvement in standard hydrologic models, and
- tools for balancing the costs of underpreparing for increasing floods versus the costs of overpreparing.

This manual describes a framework for evaluating plans and projects over a range of possible conditions. While an improvement on the common approach of designing for a single event, additional tools for balancing the costs of underpreparing versus overpreparing for floods in a future that may not be well predicted by the past are needed.

Chapter 8. Case Studies

This chapter highlights exposure, vulnerability, and risk assessment case studies that have generally used analysis methods outlined in this manual. The purpose is to demonstrate how researchers and practitioners have incorporated extreme events and climate change into assessments of exposure, vulnerability, and risk, and to provide observations related to the constantly improving state of "best actionable engineering and science methods and data."

The case studies are roughly listed in order of increasing level of analysis and include elements for the indicated level:

- Bridge 02315 (Barkhamsted, CT) – Level 2 analysis using the NRCS unit hydrograph and multiple historical precipitation data sources.
- USGS Regression Analysis for New York and Vermont – Level 4 analysis including the development of new regional regression equations for discharge projections.
- Minnesota Pilot Project – Level 4 analysis using the NRCS unit hydrograph and projected precipitation data.
- Gulf Coast 2: Airport Boulevard Culvert – Level 5 analysis using the NRCS unit hydrograph procedure with regression equations and custom climate projections for a small watershed.
- Cedar and South Skunk River Iowa Pilot – Level 5 analysis using advanced hydrologic models and custom climate projections on large watersheds.

8.1. Bridge 02315 (Barkhamsted, CT)

The Barkhamsted Bridge 02315 case study was completed by the Connecticut Department of Transportation partially funded by a grant from the FHWA (Connecticut Department of Transportation 2014). The case study is an example of a level 2 analysis using the NRCS unit hydrograph method as the primary hydrologic design tool and two historical precipitation data sets.

8.1.1. Background and Results

Bridge 02315 carries Route 44 over an unnamed waterway discharging to Morgan Brook in Barkhamsted. Route 44 is classified by the state DOT as a "Rural Principal Arterial" with two lanes of traffic in the vicinity of the bridge. Figure 8.1 shows the location as indicated by the circle.

The structure is a three-sided concrete box culvert 7.5 feet wide, 8 feet high, and 60 feet long. Figure 8.2 shows the inlet of the culvert, which at the time of the study had been in place for approximately 66 years. Under the state DOT design criteria, the state classifies the location as an "intermediate structure" because the watershed is greater than one square mile. The state requires that Intermediate structures be: 1) designed to pass a 100-year event and 2) evaluated at the 500-year check event.

The drainage area is 1.48 square miles with a majority of the drainage area in woodlands with some residential structures. About 8 percent of the watershed is characterized as swampy land. The NRCS unit hydrograph methodology with 24-hour precipitation values were used to estimate peak flows.

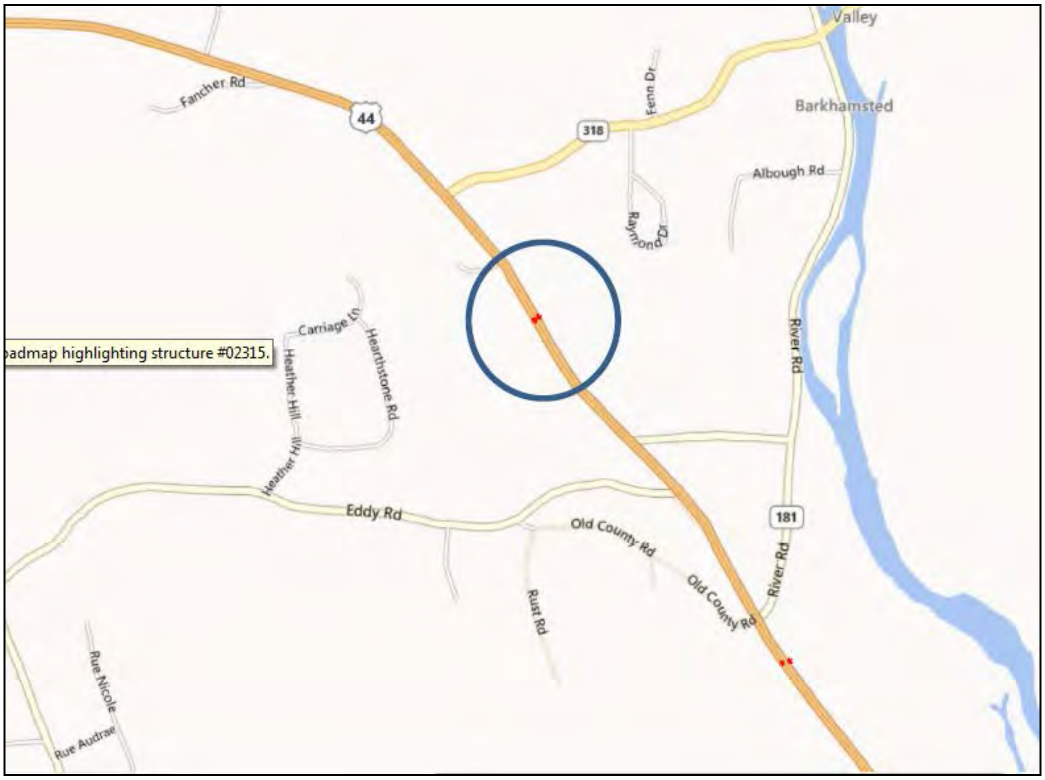

Figure 8.1. Bridge 02315 location map.

Figure 8.2. Inlet of Bridge 02315.

The study team applied two different historical rainfall datasets to the NRCS unit hydrograph model. TP-40 provides precipitation at different frequencies, but does not include data for the past several decades (Herschfield 1961). The second dataset, referred to as Precip.net, is much newer and includes data through 2008 (Northeast Regional Climate Center 2014).

Table 8.1 summarizes the peak discharges estimated using these two datasets for the 100-year design discharge and 500-year check discharge. The study team estimated that overtopping of this culvert begins at a discharge of approximately 610 cfs. The study team concludes “the structure cannot convey the estimated Precip.net 100-year frequency design event flows.”

Table 8.1. Peak Discharges at Bridge 02315.

Return Period	Peak Discharge TP-40 (ft^3/s)	Peak Discharge Precip.net (ft^3/s)
100-year	580	970
500-year	900	1620

8.1.2. Observations

The study team applied standard data sources (TP-40) and hydrologic techniques (NRCS unit hydrograph) to estimate design and check discharges for a small watershed (1.48 square miles). They recognized that historical trends in precipitation had been occurring and that newer historical precipitation summaries (Precip.net) indicated higher precipitation values that would increase projected design discharges. Additional analyses for a more robust level 2 analysis could include the following:

- a quantitative trend analysis of historical precipitation to identify the significance of the historical trend,
- development or identification of confidence limits on the TP-40 and Precip.net 100-year and 500-year precipitation to estimate the range of flows associated with the confidence limits and the degree of overlap of the two confidence intervals,
- as required in the state drainage criteria, evaluation of the consequences of the overtopping discharges,
- estimate the remaining service life of the culvert, and
- develop mitigation alternatives given the risks of overtopping for the remaining service life of the culvert.

Although the Precip.net 100-year flow appears not to meet the current design criterion of “passing” the 100-year design discharge, enlarging or replacing the culvert may not be the most cost-effective approach to address the risks. The risk assessment might include the following considerations:

- What are the impacts of overtopping? Are the damages severe? Could mitigation such as embankment armoring or temporary road closures mitigate the damages?
- For the remaining service life, what is the probability of experiencing an overtopping event? Is this probability acceptable considering other demands for resources?
- Does the trend analysis indicate further increases in precipitation are likely during the remaining service life?

8.2. USGS Regression Analysis for New York and Vermont

This case study is an example of a level 4 analysis primarily because climate projections were used. An important feature of this study is the attempted development of regional regression equations that could be used to estimate projected discharges at ungaged basins.

In cooperation with the New York State Department of Transportation, the USGS developed new regression equations and a web-based tool based on the USGS StreamStats Program for estimating current and future flows in ungaged basins under various climate change scenarios (Burns et al., 2015). The tools apply for any stream in New York State (exclusive of Long Island) and the Lake Champlain Basin of Vermont.

For New York, the approach incorporates previously developed regression equations by Lumia *et al*. (2006) that include a climate-related variable. In that work, the state is divided into six hydrologic regions with mean annual precipitation as the climatic variable in two regions and mean annual runoff as the climatic variable in the other four regions. (Annual runoff is the difference between annual precipitation and annual evapotranspiration (ET)).

For Vermont, the approach uses the previously developed regression equation by Olson (2014). In Vermont, there is only one set of equations with average annual precipitation as the climatic variable in the regression equations.

The tool is based on the following data and assumptions:

- projections of future annual precipitation from five climate models from the CMIP5 project and two greenhouse gas emission scenarios (RCP 4.5 and RCP 8.5),
- five climate models were selected based on discussions with climate scientists on the climate models that best represent historic trends in precipitation in the Lake Champlain Basin (Guilbert *et al.* 2014),
- results were averaged over three future periods: 1) 2025 to 2049, 2) 2050 to 2074, and 3) 2075 to 2099,
- assumed that the relation between annual precipitation or runoff and the peak flows will be the same in future as they were for the time periods for the which the regression equations were developed, and
- assumed that the ET to precipitation ratio was held constant so that future changes in annual runoff are governed by changes in precipitation and the resulting changes in ET.

Burns *et al*. (2015) discuss several sources of uncertainty in this approach including uncertainty in the peak flow estimates, inaccuracies in determining the prediction variables, uncertainty embedded in each climate model and emission scenario, and uncertainties in downscaling from the GCMs.

Preliminary results for this study indicate that the larger increases in x-percent chance discharges are projected for the near future period 2025-2049 for the low gas emission scenario RCP 4.5 than for the period 2050-2074 and the high gas emission scenario RCP 8.5 (Wayne Gannett, New York State DOT, written communications, January 11, 2016). These results are difficult to rationalize. Possible reasons for the apparent irrational results include:

- the regression equations may be extrapolated too far beyond the precipitation data on which they are based and give irrational results for the 2050–2074 period and RCP 8.5,
- the projected precipitation data are based on a mean of five GCMs and the projected precipitation is not reasonable, or

- comparisons of regression estimates based on projected model precipitation to regression estimates based on historical precipitation and runoff for the period 1951–80 are contributing to the irrational results.

Burns *et al*. (2015) note that this approach has not been adequately tested or validated. It appears additional testing is needed before this method should be recommended.

8.3. Minnesota Pilot Project

A FHWA-funded Minnesota pilot study focused on two Minnesota Department of Transportation (MnDOT) districts that experienced severe flooding in recent years (Minnesota DOT 2014). This pilot project is an example of a level 4 analysis using the NRCS unit hydrograph model with projected precipitation data. The two sites analyzed to evaluate the potential effects of climate change were:

- District 1 (Northeast Minnesota), MN 61 culvert (#5648) over Silver Creek, a 19.65 square mile stream in the Superior Uplands that drains into Lake Superior, and
- District 6 (Southeast Minnesota), US 63 culvert (#5722) over Spring Valley Creek, a 13.93 square mile stream in southeastern Minnesota.

The data and methodology used in these two studies included:

- Output from 22 GCMs was queried to provide a broad range of possible future precipitation for three greenhouse gas emission scenarios (RCP 4.5, RCP 6.0, and RCP 8.5) from the CMIP5 project.
- The projections of future climate using daily precipitation from the GCMs were translated to the nearest weather station for the two watersheds for 2040, 2070, and 2100 using the software tool SimCLIM.
- Precipitation frequency curves were developed for the 24-hour storm duration from historical data at the nearby weather stations using NOAA Atlas 14.
- Precipitation frequency curves were developed for the 24-hour duration storm using GCM data for current and future (2040, 2070, and 2100) conditions for the 22 models and the percent changes were estimated.
- The median percent change was calculated and applied to the historical data based on the NOAA Atlas 14 analysis to obtain future (2040, 2070, and 2100) x-percent chance precipitation for each emission scenario.
- Flood frequency curves for current and future (2040, 2070, and 2100) conditions were developed using the x-percent AEP precipitation values in the Natural Resources Conservation Service WinTR-20 watershed model.
- Future land use was included in the WinTR-20 analysis assuming a build-out of current zoning.

The results of the WinTR-20 analysis are summarized for the 1-percent chance event:

- MN 61 culvert (#5648) over Silver Creek: the percent increase in the 1-percent chance 24-hour precipitation ranged from 3.8 to 32.4 percent across the three emission scenarios and three time periods; the corresponding increase in the 1-percent chance discharge ranged from 16 to 60 percent.
- US 63 culvert (#5722) over Spring Valley Creek: the percent increase in the 1-percent chance 24-hour precipitation ranged from 3.2 to 27.1 percent across the three emission

scenarios and three time periods; the corresponding increase in the 1-percent chance discharge ranged from 5 to 36 percent.

Because the existing structures do not meet the design criteria under all climate scenarios, the study authors developed adaptation alternatives.

8.4. Gulf Coast 2: Airport Boulevard Culvert

As part of the much larger Gulf Coast study (Phase 2) funded by the U.S. Department of Transportation, engineering analyses and assessments of the potential risks associated with climate change were conducted on various transportation assets in the Mobile, Alabama region (Parsons Brinkerhoff 2014). The culvert at the Airport Boulevard crossing of Montlimar Creek is the subject of this case study. This is an example of a level 5 analysis using custom projections of climate developed by a climate scientist for the project. The hydrologic tools were the NRCS unit hydrograph with regression equations for calibration on a small watershed.

8.4.1. Background

The purpose of the engineering analysis and assessment was to evaluate whether the existing culvert is sufficient under future scenarios of more intense land use and projected increases in 24-hour precipitation resulting from climate change. The culvert site is located in the Mobile, Alabama metropolitan area and indicated by the red star in Figure 8.3. It is located immediately west from Interstate 65 and has a 3.3 mi^2 drainage area. Airport Boulevard is a major arterial street linking downtown Mobile with its western suburbs and the regional airport. It carries six lanes of traffic plus additional frontage road lanes.

The existing culvert conveys Montlimar Creek flows under Airport Boulevard through four concrete box culvert cells each with a rise of 8 feet and a span of 12 feet. The main channel of Montlimar Creek is an artificial trapezoidal channel. The culvert is shown in Figure 8.4. The applicable design standard for this culvert is to pass a 25-yr flood with no less than 2 feet of freeboard measured from the roadway edge of pavement. The standard is for the City of Mobile and is derived from the standards of the Alabama Department of Transportation.

8.4.2. Methodology and Results

The case study followed a general process for transportation facility adaptation assessments. This process provides an 11-step framework for determining the vulnerabilities of an individual transportation facility to climate change, developing adaptation options to mitigate risks of anticipated changes, and selecting a course of action. The 11 steps are:

1. describe the site context,
2. describe the existing / proposed facility,
3. identify climate stressors that may affect infrastructure components,
4. decide on climate scenarios and determine the magnitude of changes,
5. assess performance of the existing / proposed facility,
6. identify adaptation option(s),
7. assess performance of the adaptation option(s),
8. conduct an economic analysis,
9. evaluate additional decision-making considerations,

10. select a course of action, and
11. plan and conduct ongoing activities.

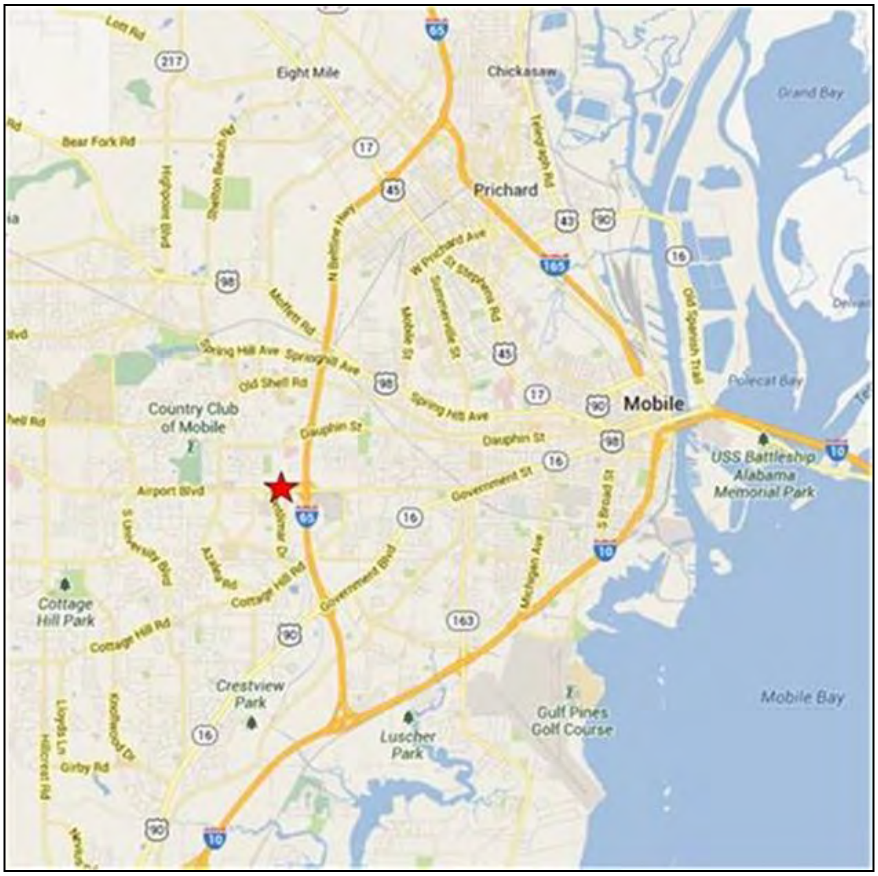

Figure 8.3. Airport Boulevard culvert location map.


Figure 8.4. Airport Boulevard over Montlimar Creek from upstream.

The part of the assessment reviewed here focuses on the analytical activities from steps 4 through 10.

Five 24-hour rainfall depths were used in the analyses. The base case rainfall depths were computed from five area rain gages over the 30-year period from 1980 through 2009. This period was chosen, in part, because the same period is used as a baseline for the GCMs from which projected rainfall estimates where obtained. NOAA atlas 14 (NOAA 2013) was used to obtain two additional estimates based on historic rainfall data: 1) the mean estimate and 2) the 90 percent upper confidence estimate. The mean is considered the best estimate of the true value of the 24-hour precipitation depth (assuming nonstationarity) while the 90 percent upper confidence estimate is an estimate for which there is a 10 percent chance that the true value of the 24-hour precipitation depth is greater.

Two estimates were also obtained from GCMs: 1) a "wetter" scenario and 2) a "drier" scenario. Overall, 20 combinations of emission scenarios and models were available. It was assumed that each combination was equally likely and that these combinations are representative of future scenarios. With these assumptions, the 5 percent and 95 percent projections of 24-hour rainfall depths were calculated. The 5 percent value – meaning there is a 5 percent probability that the estimate could be lower – was designated as the "drier" scenario. The 95 percent value was taken as the "wetter" scenario.

Table 8.2 summarizes the 24-hour precipitation values for selected storm events. (The 25-yr event was not directly available from the GCMs and was interpolated.) Comparison of the two historical data estimates – the observed and the NOAA baseline – illustrates uncertainty present even in using historical data. These estimates differ because each uses different measurement years, gages, and methodologies.

Table 8.2. 24-Hour precipitation depths used for the Airport Boulevard culvert analyses.

24-hour Storm Event Return Period*	Observed (Model Baseline) 1980-2009 (inches)	NOAA Average Baseline (inches)	NOAA 90% Upper Confidence Limit (inches)	"Wetter" Narrative 2070-2099 (inches)	"Drier" Narrative 2070-2099 (inches)
100-yr storm	13.5	14.9	18.9	22.3	13.4
50-yr storm	12.5	12.8	15.9	20.2	12.5
25-yr storm	10.1**	10.9	13.4	16.7**	9.9**
10-yr storm	8.5	8.6	10.1	13.7	8.4

*Adapted from Table 5 (Parsons Brinkerhoff 2014).
**Interpolated values.

Another comparison worth noting is moving from historical data to projected data based on the GCMs. Implicit in the NOAA data (baseline and 90 percent upper confidence limit) is a standard deviation of 3.9 inches in the rainfall estimates. Similarly, implicit in the wetter and drier scenarios are a mean of 17.8 inches and a standard deviation of 2.7 inches. Therefore, the best estimate of the increase from historical 24-hour precipitation levels is 20 percent (from 14.9 to 17.8 inches) with the variability around that estimate decreasing from a standard deviation of 3.9 to 2.7.

The SCS TR-20 model within the Win TR-20 computer program was chosen to estimate existing and future peak flows. The model is based on the 24-hour rainfall estimate and the land use/land cover expressed in a curve number.

Initial flow estimates generated from the TR-20 model were much greater than estimates from the applicable urban regression equations for the area (Hedgecock and Lee 2010). Therefore, the study authors calibrated the TR-20 estimates of existing flows downward to be within one standard error of the estimate for the regression equation. Table 8.3 provides the resulting flow estimates after calibration.

Table 8.3. TR-20 projected peak flows at the Airport Boulevard culvert.

24-hour Storm Event Return Period*	Observed 1980-2009 w/ Current LU (ft^3/s)	Observed 1980-2009 w/ Future LU (ft^3/s)	NOAA 90% Upper Conf. Limit w/ Future LU (ft^3/s)	"Wetter" Narrative w/ Future LU 2070-2099 (ft^3/s)	"Drier" Narrative w/ Future LU 2070-2099 (ft^3/s)
100-yr storm	4,360	4,480	6,550	7,840	4,450
50-yr storm	3,980	4,100	5,400	7,050	4,100
25-yr storm	3,050	3,170	4,450	5,710	3,130
10-yr storm	2,420	2,550	3,170	4,560	2,510

*Adapted from Table 8 (Parsons Brinkerhoff 2014).

Two future changes were considered in these analyses: 1) increased development (future land use) and 2) increased precipitation because of climate change. By comparing the estimates based on the observed precipitation values from 1980 to 2009, future land use results in peak flows that range from 3 to 5 percent higher than current land use depending on the return period considered. Therefore, for this watershed the change in land use is not a significant contributor to changes in flows. However, comparing the wetter narrative estimated peak flows to the flow based on observed precipitation (future land use), the flows range from 72 to 80 percent greater indicating a large potential increase. Conversely, the equally likely drier narrative suggests no change in peak flow.

Then, hydraulic analyses were conducted to assess the performance of the culvert under current and future flows using the HY-8 program developed and supported by the FHWA. Figure 8.5 displays the culvert performance curve for the existing culvert. Also shown are the elevations of the roadway low point at which overtopping would begin to occur and the maximum elevation allowed under the design criterion of 2 ft of freeboard. (The criterion is from edge of pavement not low point, but this inconsistency is not critical for illustrating the approach in this case study.)

The figure also demonstrates that under existing conditions, the culvert satisfies the design criteria. However, other 25-yr return period scenarios do not. Because Montlimar Creek at this location is in a FEMA floodplain, the potential effects of the 100-yr flood are relevant. For comparison, a 100-yr scenario discharge is also included on the figure.

The next step of the analysis was to identify potential adaptation options whose cost and performance could be compared with the no action alternative. The options considered were:

- Increase number of culvert cells from 4 to 6 (option 1).
- Increase size of culvert cells from 12 ft x 8 ft to 21 ft x 9 ft (option 2).
- Implement regional drainage area management practices.
- The last option included strategies that would reduce runoff from the watershed rather than increase the capacity of the culvert. Although a potentially viable option, it was not evaluated in depth by the study authors.

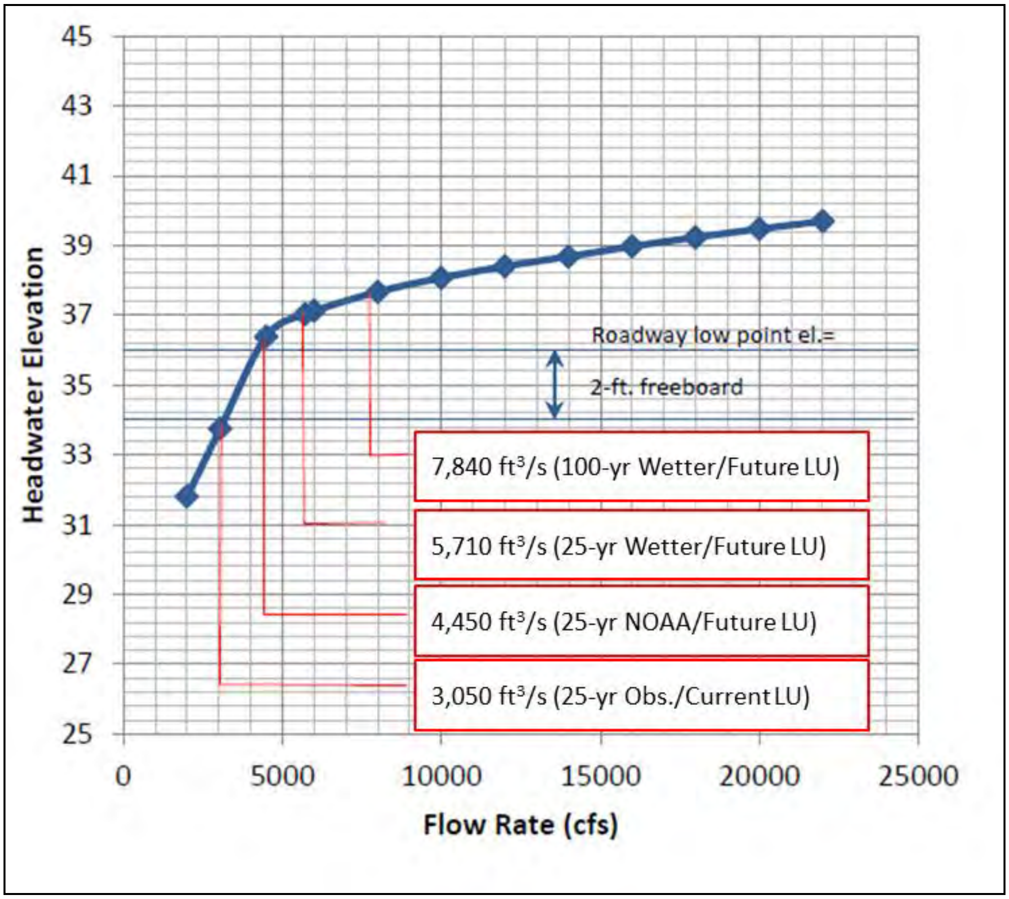

Figure 8.5. Performance curve for existing Airport Boulevard culvert.

Flooding effects on traffic and property damage were evaluated for a range of flood elevations. Then, an economic analysis of adaptation options was conducted using a Monte Carlo process and compared to the no action alternative. Selected results for adaptation option one are summarized in Table 8.4 for five climate change scenarios for the 90th percentile of the Monte Carlo simulations. The 90th percentile means that of the 1,000 Monte Carlo simulations only 10 percent had worse flooding avoided (higher benefits). Statistically, the expected outcome would correspond to the 50th percentile simulation.

For each climate scenario, the present value of the costs - the expansion of the culvert by two cells – is the same. The present value of the benefits, however, depends on the precipitation and flooding expected under each scenario. As would be expected, the greatest benefit ($12.7 million) would occur for the most severe flooding scenario (the wetter narrative). The net present value (NPV) is the difference between the benefits and the costs while the benefit cost ratio (BCR) is the ratio of the benefits to the cost. The benefit cost ratio should be greater than one if the proposed investment is to be justified. Of the 1000 Monte Carlo runs, the table also reports the percentage of the simulations for which the BCR was greater than 1. A similar analysis was performed for adaptation option two, but those results have not been included here.

The study authors then averaged the results from the 5 climate scenarios as is also shown in Table 8.4. The average numbers were then used to support decision making assuming that each of the five scenarios is equally likely.

Table 8.4. Economic analysis results (90th percentile) for adaptation option one.

Description of Climate Scenario*	1. Observed 1980-2009 w/ Current LU	2. Observed 1980-2009 w/ Future LU	3. NOAA 90% Upper Conf. Limit w/ Future LU	4. “Wetter” Narrative w/ Future LU 2070-2099	5. “Drier” Narrative w/ Future LU 2070-2099	Average of All Scenarios
Present Value of Costs	$1.7m	$1.7m	$1.7m	$1.7m	$1.7m	$1.7m
Present Value of Benefits	$3.5m	$4.0m	$6.8m	$12.7m	$3.0m	$6.0m
Net Present Value	$1.8m	$2.2m	$5.0m	$11.0m	$1.3m	$4.3m
Benefit Cost Ratio (BCR)	2.0	2.3	3.9	7.3	1.7	3.5
Probability that BCR > 1	36%	39%	68%	97%	30%	NA**

*Adapted from Table 13 (Parsons Brinkerhoff 2014).
**Not applicable.

The final step of the case study was to formulate the recommendations for adaptation. The study acknowledged that such decisions should involve affected stakeholders and likely would consider numerous qualitative factors that were not part of the study methodology. Given these caveats, the study authors recommended that alternative option one was a prudent course of action in light of the possibility of climate change.

8.4.3. Observations

This case study is a good example of the application of several of the techniques described in this manual, but it also illustrates areas where improvement is possible. The most important areas where the study exemplifies good practice are:

1. use of downscaled precipitation values from credible sources available at the time at a temporal and spatial scale appropriate for the engineering models selected,
2. selection and application of appropriate hydrology and hydraulic models for the study objective, and
3. application of a general framework for a risk analysis that quantifies traffic and flood damage costs consistent with previous FHWA guidance.

The case study authors used downscaled projections from ten models over three climate scenarios prepared by a professional experienced in such activities. Use of multiple models and multiple scenarios to generate a range of outputs is highly recommended. In addition, the type of precipitation data needed was the 24-hour duration, which is sufficiently long to be effectively generated from the GCM/RCMs.

The primary hydrology and hydraulic tools included GIS databases of land use and soil types, the TR-20 hydrology model, USGS regression equations for peak flows, and the HY-8 culvert model for culvert hydraulics. All of these represent appropriate industry-standard tools.

Finally, the study authors used a fairly comprehensive framework for including capital costs for culvert construction under the two adaptation options as well as traffic delay costs and flooding damages. Although details of the sources and computations were not provided, the framework appeared consistent with methods recommended (Cory *et al.* 1981).

A major area for improvement in the study is to better quantify the uncertainty associated with each step of the analysis so that unknown levels of conservativism do not become embedded in the results and, therefore, within recommendations. The areas where conservativism was introduced include:

- selecting a conservative rainfall distribution from those created by NOAA (90th percentile of the 4th quartile),
- calibrating the TR-20 model to the regression equation estimates plus one standard error, and
- relying on the 90th percentile damage estimate and ignoring the equally likely 10th percentile damage estimate.

Combining the 90th percentile rainfall distribution with the 90th percentile damage estimates results in an outcome that is expected to be worse with only a one percent probability (99th percentile) provided they are independent. By accumulating the effects of conservative assumptions at each decision point in an analysis, the rarity of the outcome increases geometrically. While such outcomes may be relevant for decision-making, it is fundamental to also understand the most likely outcomes. In this case, the most likely outcome would be estimated by taking the 50th percentile rainfall distribution and the 50th percentile damage estimates. From this outcome, and the more extreme outcomes, a distribution of outcomes can be generated. ***The planner/designer should establish the appropriate level of conservatism, then, considering the end result of the process rather than at each stage of the process.***

In addition, calibration of the TR-20 model with the regression estimates dramatically lowered the current land use conditions flow using the observed precipitation from 10,000 ft^3/s to 4,300 ft^3/s. Such a sharp lowering of the peak flow in calibration raises questions about whether the effects of upstream storage and culverts have been fully accounted for. This lowering overshadows the conservative selection of the 90th percentile NOAA distribution. Further, calibration to the regression estimate plus one standard error is equivalent to calibrating to the 84th percentile confidence limit. The study authors did not provide a justification regarding why calibrating to that discharge was appropriate.

A second area of improvement is to consider specifically the accepted risks in the current design standards and how those design standards distribute those risks to other facilities. Adaptation upgrades should not be considered in isolation. Damages and potential adaptation investments at culverts upstream and downstream of the subject culvert, as well as other area culverts responding to the same changes in precipitation should be considered to invest wisely in adaptation improvements.

A third important area to consider is placement of the uncertainty of climate change within the context of the hydrologic uncertainty that is (or should be) already recognized. As discussed previously with the 24-hour precipitation estimates, the NOAA upper and lower confidence limits are based on historical data while the wetter and drier narratives are based on projected climate change. The best estimate (expected value) of the increase from historical 24-hour precipitation levels to climate changes estimates is 20 percent (from 14.9 to 17.8 inches) and for the expected value plus one standard deviation (84th percentile) from 18.8 to 20.5 inches (9 percent increase). It would not be appropriate to compare the historical mean (14.9 inches) with the wetter scenario (22.3 inches) and reference that as the effect of climate change.

In addition, other aspects of this case study form the basis for improving future studies:

- Consider using hydrologic models that include information about the uncertainty of flow estimates. While the TR-20 rainfall/runoff model is commonly used and provides the ability to incorporate future land uses and climate change, it has no error or uncertainty bands associated with it and it is generally considered conservative.
- Include the equally likely NOAA 10 percent lower confidence limit in addition to the NOAA 90 percent upper confidence limit in the analysis.
- Average appropriate scenarios that represent equivalent likelihoods. For the economic analysis, the study authors averaged a mix of current and future land use scenarios and an assortment of mean and extreme climate scenarios that could not reasonably be assumed to be equally likely and represent the range of possible outcomes.
- Consider longer asset lifetimes than 30 years for culverts. Though this may be a reasonable expectation, major rehabilitation or replacement expenses often occur much later. However, with the discount rate used in the study (7 percent), this may not be a significant factor.
- Use projected data consistent with the asset lifetime. In this study, end of century precipitation values were used when the asset was not expected to reach the end of the century (30-yr asset lifetime). Mitigating this observation in this case is that near- and mid-century precipitation projections were roughly equivalent to the end-of-century projections. However, this raises another question about whether the climate projection represents a sudden shift in precipitation rather than a gradual increase over time.

8.5. Cedar and South Skunk River Iowa Pilot

This case study is an example of a level 5 analysis using advanced hydrologic modeling tools and customized climate projections developed by a climate scientist for the project. The Iowa Department of Transportation conducted an FHWA-funded pilot study of six bridges in two Iowa river basins – the Cedar River Basin (7,753 square miles) and the South Skunk River Basin (813 square miles) – to develop a methodology to evaluate their vulnerability to climate change and extreme weather (Anderson *et al.* 2015). The six bridges had been either closed or severely stressed by record flooding within the past seven years.

The data used in these analyses included daily precipitation data for 19 climate projections from 9 climate models for three greenhouse gas emission scenarios (seven A1B, three A1F1, and nine A2) from the CMIP3 project. These climate projections of daily precipitation were downscaled to a one-eighth-degree grid (approximately 12 km by 12 km) using the asynchronous regional model (ARRM) (Stoner *et al.* 2013) and used in the distributed watershed model CUENCAS (Mantilla and Gupta 2005) to obtain 19 estimates of flood discharges for the six bridges for the period 1960 to 2099. Accuracy of downscaled data was evaluated by comparison of model estimates of the annual maximum precipitation to historical data for the period 1960-1999.

Flood frequency curves were developed for the Cedar River and South Skunk River Basins for the two periods 1960-2009 and 1960-2059 using the median of the 19 projected model estimates. Flood frequency curves for one location in each watershed are shown in Figure 8.6 for the two periods. Both flood frequency curves can be used to estimate the increase in flood discharges by accounting for future climate change. The frequency curve for future conditions (1960-2059) is the blue solid line with the upper and lower 95 percent confidence limits based on the median of the 19 climate projections represented by the dotted lines. The shaded area in the figure represents the upper and lower 95-percent confidence limits for the period 1960-2009.

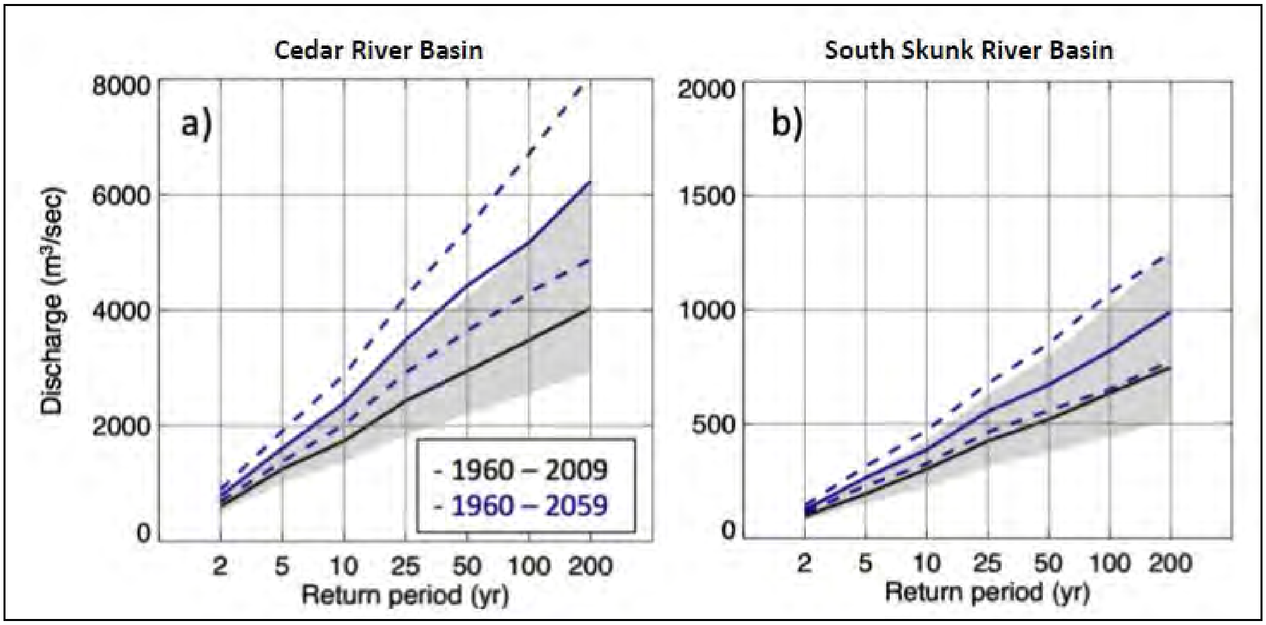

Figure 8.6. Frequency curves for the Cedar River and South Skunk River basins.

Anderson *et al*. (2015) concluded that, with climate change, all six critical interstate and highway locations would be exposed to streamflow that exceeds current design capacity. Bridge and highway resilience would need to be improved in four of the six pilot bridge locations to withstand the projected increase in the frequency of extreme streamflow.

This effort may be considered an example of a level 5 analysis. Specific climate science expertise was secured to select the GCMs, emission scenarios, and downscaling appropriate for the study. In addition, a custom rainfall/runoff model was applied to each of the watersheds.

References

23 CFR 650 subpart A (1979). "*Location and Hydraulic Design of Encroachments on Flood Plains*," November 26.

44 CFR 60.3 (1976). "*Floodplain Management Criteria for Flood-Prone Areas*," October 26.

AASHTO (2014). AASHTO Drainage Manual, 1st edition. Volume 1.

AECOM, Michael Baker, Jr., Inc., and Deloitte Consulting, LLP (2013). "The Impact of Climate Change and Population Growth on the National Flood Insurance Program Through 2100," prepared for the Federal Emergency Management Agency, (http://www.aecom.com/News/Sustainability/FEMA+Climate+Change+Report).

Anderson, C., D. Claman, and R. Mantilla (2015). *Iowa's Bridge and Highway Climate Change and Extreme Weather Vulnerability Assessment Pilot*, Final Report HEPN–707, Institute for Transportation, Iowa State University, Ames, Iowa.

Asquith, W. H. and D. B. Thompson (2008). Alternative Regression Equations Based on Drainage Area and Mean Annual Precipitation for Estimation of Annual Peak-Streamflow Frequency for Undeveloped Watersheds in Texas Using PRESS Minimization, Scientific Investigations Report 2008–5084, U.S. Geological Survey.

Asquith, W.H. and M. C. Roussel (2009). "Regression Equations for Estimation of Annual Peak-Streamflow Frequency for Undeveloped Watersheds in Texas Using an L-moment-Based, PRESS-Minimized, Residual-Adjusted Approach," SIR 2009-5087, USGS.

Barros, A. P., Y. Duan, J. Brun, and M. A. Medina, Jr. (2014). "Flood Nonstationarity in the Southeast and Mid-Atlantic Regions of the United States," Journal of Hydrologic Engineering, 19(10).

Bonnin, Geoffrey M., Kazungu Maitaria, and Michael Yekta (2011). "Trends in Rainfall Exceedances in the Observed Record in Selected Areas of the United States," Journal of the American Water Resources Association (JAWRA), 46(2): 344-353. DOI: 10.111/j.1752-1688.2011.00603.

BPR (1956). "Policy on Interstate System Projects," PPM 20-4, August 10, 1956.

Burns, D.A., M.J. Smith, and D.A. Freehafer (2015). "Development of Flood Regressions and Climate Change Scenarios to Explore Estimates of Future Peak Flows". U.S. Geological Survey Open-File Report 2015-1235, 11 p.

Clarke, LE, JA Edmonds, HD Jacoby, H Pitcher, JM Reilly, and R Richels (2007). Scenarios of greenhouse gas emissions and atmospheric concentrations. Sub-report 2.1a of Synthesis and Assessment Product 2.1. Climate Change Science Program and the Subcommittee on Global Change Research, Washington DC.

Clarke, R. (1973). "A Review of Some Mathematical Models Used in Hydrology, with Observations on Their Calibration and Use," *Journal of Hydrology,* 19, 1–20.

Cleveland, T. G., D. B. Thompson, and X. Fang (2011). *Use of the Rational and Modified Rational Method for Hydraulic Design*, Final project report 0–6070–1, Texas Department of Transportation, Texas Tech University, Lubbock, Texas.

Cohn, T. A., Lane, W. L., and Stedinger, J. R. (2001). "Confidence Intervals for Expected Moments Algorithm Flood Quantile Estimates," Water Resources Research, 37(6):1695–1706.

Cohn, T.A. and H.F. Lins (2005). “Nature’s Style: Naturally Trendy”, Geophysical Research Letters, Vol. 32, L23402, doi: 10.1029/2005GL024476.

Connecticut Department of Transportation (2014). “Climate Change and Extreme Weather Vulnerability Pilot Project,” Final Report, December.

Corry, M.L., J.S. Jones, and P.L. Thompson (1981). “*Design of Encroachments on Flood Plain Using Risk Analysis*,” Hydraulic Engineering Circular 17 (HEC-17), April.

Dawdy, D. R., V. W. Griffis, and V. K. Gupta (2012). “Regional Flood Frequency Analysis: How We Got Here and Where Are We Going,” *Journal of Hydrologic Engineering*, 17(9), 953–959.

Dettinger, M.D. and D.R. Cayan (1995). “Large-Scale Atmospheric Forcing of Recent Trends Toward Early Snowmelt Runoff in California”. Journal of Climate 8: 606-623.

Douglass, Scott L. and Joe Krolak (2008) “*Highways in the Coastal Environment,*” Hydraulic Engineering Circular 25 (HEC-25), 2nd ed., FHWA-NHI-07-096.

Douglass, Scott L., Bret M. Webb, and Roger Kilgore (2014), “*Highways in the Coastal Environment Volume 2*,” Hydraulic Engineering Circular 25 (HEC-25), October.

Environmental Protection Agency (2009). “Land-Use Scenarios: National-Scale Housing-Density Scenarios Consistent with Climate Change Storylines”. Global Change Research Program, National Center for Environmental Assessment, Washington, DC, EPA/600/R-08/076F.

Executive Order No. 11296 (1966). “*Evaluation of Flood Hazard in Location Federally Owned or Financed Buildings, Roads, and Other Facilities, and in Disposing of Federal Lands and Properties*,” August 10.

Executive Order No. 11988 (1977). “*Floodplain Management*,” May 24.

Executive Order No. 13653 (2013). “*Preparing the U.S. for the Impacts of Climate Change*,” 3 C.F.R. pps 66819-66824.

Executive Order No. 13690 (2015). “*Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input*,” January 30.

Federal Emergency Management Agency (FEMA) (1983). The 100-year Base Flood Standard and the Floodplain Management Executive Order: A review prepared for the Office of Management and Budget by the Federal Emergency Management Agency: Federal Emergency Management Agency, September.

FHWA (2012a) "Eligibility of Activities to Adapt To Climate Change and Extreme Weather Events Under the Federal-Aid and Federal Lands Highway Programs." Memorandum dated September 24, 2012 by J. Baxter, G. Shepard and J. Curtis.

FHWA (2012b) "*Climate Change and Extreme Weather Vulnerability Assessment Framework,*" FHWA-HEP-13-005 (see http://www.fhwa.dot.gov/environment/climate_change/adaptation/resources_and_publications/vulnerability_assessment_framework/index.cfm)

FHWA Order 5520 (2014). “Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events,” December 15.

FHWA (2013). “Climate Variability and Change in Mobile, Alabama - Final Report Task 2,” Impacts of Climate Change and Variability on Transportation Systems and Infrastructure – The Gulf Coast Study, Phase 2, FHWA-HEP-12-053, June.

Friedman, D., J. Schechter, B. Baker, C. Mueller, G. Villarini, and K.D. White. (2016). US Army Corps of Engineers Nonstationarity Detection Tool User Guide. US Army Corps of Engineers: Washington, DC.

Fujino, J, R Nair, M Kainuma, T Masui, and Y Matsuoka (2006). Multigas mitigation analysis on stabilization scenarios using aim global model. The Energy Journal Special issue #3:343–354.

Groisman, P.Y., R.W. Knight, D.R. Easterling, T.R. Karl, G.C. Hegerl, and V.N. Razuvaev (2005). “Trends in Intense Precipitation in the Climate Record”, Journal of Climate 18:1326-1350. doi:10.1175/JHM-D-11-039.1.

Guilbert, J., B. Beckage, J.M. Winter, R.M. Horton, T. Perkins, and A. Bomblies (2014). “Impacts of Projected Climate Change over the Lake Champlain Basin in Vermont”. Journal of Applied Meteorology and Climatology, Vol. 53, pp. 1861-1875.

Hayhoe, Katharine and Anne Stoner (2012). *Temperature and Precipitation Projections for the Mobile Bay Region, Gulf Coast Study, Phase 2,* prepared for the U.S. DOT Center for Climate Change and Environmental Forecasting, FHWA-HEP-12-055, May.

Hedgecock, T.S. and K.G. Lee (2010). “*Magnitude and Frequency of Floods for Urban Streams in Alabama, 2007*,” USGS SIR 2010-5012.

Helsel, D.R. and R.M. Hirsch (1992). “Statistical Methods in Water Resources”. Elsevier, New York, 522 pp.

Hershfield, D. M. (1961). Rainfall Frequency Atlas of the United States for Durations of 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years, Technical Paper 40, U.S. Department of Commerce, Weather Bureau, Washington, D.C.

Hijioka, Y, Y Matsuoka, H Nishimoto, T Masui, and M Kainuma (2008). Global GHG emission scenarios under GHG concentration stabilization targets. J Glob Environ Eng 13:97–108.

Hirsch, R.M. (2011). “A Perspective on Nonstationarity and Water Management”, Journal of the American Water Resources Association 47(3): 436–446. DOI: 10.1111/j.1752-1688.2011.00539.

Hodgkins, G.A., R.W. Dudley, and T.G. Huntington (2003). “Changes in the Time of High River Flows in New England over the 20th Century”. Journal of Hydrology, Vol. 278, pp. 242-250.

Interagency Advisory Committee on Water Data (1982). “Guidelines for Determining Flood Flow Frequency,” Bulletin 17-B of the Hydrology Subcommittee, U.S. Geological Survey, Office of Water Data Coordination.

IPCC (2007*). Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC (2013). *Summary for Policymakers.* In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://www.climatechange2013.org/images/report/WG1AR5_SPM_FINAL.pdf

Karl, T.R. and R.W. Knight (1998). “Secular Trends of Precipitation Amount, Frequency, and Intensity in the USA”. Bulletin of the American Meteorological Society, Vol. 79, pp. 231-241.

Kollat, J.B., J.R. Kasprzyk, W.O. Thomas, Jr., A.C. Miller, and D. Divoky (2012). “Estimating the Impacts of Climate Change and Population Growth on Flood Discharges in the United States,” Journal of Water Resources Planning and Management, Vol. 138, No. 5, September 1, 2012. DOI: 10.1061/ (ASCE) WR.1943-5452.0000233.

Konrad, C.P. (2003). “Effects of Urban Development on Floods,” USGS Fact Sheet FS-076-03, 4pp.

Kuichling, E. (1889). “The Relation Between the Rainfall and the Discharge of Sewers in Populous Districts,” Transactions, American Society of Civil Engineers 20, 1–56.

Leopold, Luna B., M. Gordon Wolman, and John P. Miller (2005). Fluvial Processes in Geomorphology, Copyright 1964, 1992, Dover Edition, 2005, Dover Publications, New York.

Lins, H.F. and J.R. Slack (2005). “Seasonal and Regional Characteristics of U.S. Streamflow Trends in the United States from 1940 to 1999,” Physical Geography, 26(6), pp. 489-501.

Lins, H.F. and T.A. Cohn (2011). “Stationarity: Wanted Dead or Alive?,” Journal of the American Water Resources Association (JAWRA) 47(3): 475-480. DOI: 10.111/j.1752-1688.2011.00542.

Lumia, R. D.A. Freehafer, and M.J. Smith (2006). “Magnitude and Frequency of Floods in New York”. U.S. Geological Survey Scientific Investigations Report 2006-5112, 152 p.

Mantilla, R. and V.K. Gupta (2005). “A GIS Numerical Framework to Study the Process Basis of Scaling Statistics in River Networks”. IEEE Geoscience and Remote Sensing Letters 2(4): 404-408.

McCuen, R.H. (1989). “Hydrologic Analysis and Design”. Prentice Hall, Englewood Cliffs, New Jersey, 867 pp.

McCuen, R.H. (2003). “Modeling Hydrologic Change – Statistical Methods”. Lewis Publishers, A CRC Press Company, 433 pp.

McCuen, Richard H., Peggy A. Johnson, and Robert M. Ragan (2002). “*Highway Hydrology*,” Hydraulic Design Series 2 (HDS 2), Second Edition, FHWA-NHI-02-001.

Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014: *Climate Change Impacts in the United States: The Third National Climate Assessment.* U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.

Minnesota Department of Transportation (2014). “MnDOT Flash Flood Vulnerability and Adaptation Assessment Pilot Project – Final Report”. Prepared Parsons Brinckerhoff and Catalysis, November 5, 2014.

Nakicenovic, Nebojsa, Joseph Alcamo, Gerald Davis, Bert de Vries, Joergen Fenhann, Stuart Gaffin, Kenneth Gregory, Arnulf Grübler, Tae Yong Jung,Tom Kram, Emilio Lebre La Rovere, Laurie Michaelis, Shunsuke Mori, Tsuneyuki Morita, William Pepper, Hugh Pitcher, Lynn Price, Keywan Riahi, Alexander Roehrl, Hans-Holger Rogner, Alexei Sankovski, Michael Schlesinger, Priyadarshi Shukla, Steven Smith, Robert Swart, Sascha van Rooijen, Nadejda Victor, and Zhou Dadi (2000). Special Report on Emissions Scenarios (SRES), IPCC, Cambridge University Press, Cambridge.

National Oceanic and Atmospheric Administration (NOAA) (1977). Five- to 60-minute Precipitation Frequency for the Eastern and Central United States. NOAA Technical Memorandum NWS HYDRO-35, Silver Spring, MD, June.

National Oceanic and Atmospheric Administration (NOAA) (2013 and other years). "Precipitation-Frequency Atlas of the United States, Volume 9 Version 2.0: Southeastern States (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi)," NOAA Atlas 14, National Weather Service. available from the Internet at http://www.nws.noaa.gov/oh/hdsc/index.html.

National Oceanic and Atmospheric Administration (NOAA) (2016). Earth System Research Laboratory, Global Monitoring Division, retrieved on 17 February 2016 from: http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html#global.

National Weather Service (NWS) (2015). Retrieved on July 28, 2015 from: http://www.nws.noaa.gov/hic/.

North Jersey Transportation Planning Authority (2012). "Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure," prepared by Cambridge Systematics, 52 p.

Northeast Regional Climate Center (2014). "Extreme Precipitation in New York and New England," Natural Resources Conservation Service, http://precip.eas.cornell.edu/.

Olson, S.A. (2014). "Estimation of Flood Discharges at Selected Annual Exceedance Probabilities for Unregulated, Rural Streams in Vermont," U.S. Geological Survey Scientific Investigations Report 2014-5078, 27 p. plus appendices.

Parsons Brinkerhoff (2014). "Engineering Assessments of Climate Change Impacts and Adaptation Measures (Task 3.2)," Impacts of Climate Change and Variability on Transportation Systems and Infrastructure – The Gulf Coast Study, Phase 2, FHWA-HEP-15-004, August.

Perry, C.A., B.N. Aldridge, and H.C. Ross (2000). "Summary of Significant Floods in the United States, Puerto Rico, and the Virgin Islands, 1970-89," U.S. Geological Survey Water-Supply Paper 2502, Reston, VA.

Peterson, T.C., Richard R. Heim Jr., Robert Hirsch, Dale P. Kaiser, Harold Brooks, Noah S. Diffenbaugh, Randall M. Dole, Jason P. Giovannettone, Kristen Guirguis, Thomas R. Karl, Richard W. Katz, Kenneth Kunkel, Dennis Lettenmaier, Gregory J. McCabe, Christopher J. Paciorek, Karen R. Ryberg, Siegfried Schubert, Viviane B. S. Silva, Brooke C. Stewart, Aldo V. Vecchia, Gabriele Villarini, Russell S. Vose, John Walsh, Michael Wehner, David Wolock, Klaus Wolter, Connie A. Woodhouse, and Donald Wuebbles (2013). "Monitoring and Understanding Changes in Heat Waves, Cold Waves, Floods, and Droughts in the United States". American Meteorological Society, pp. 821-834, June.

Pettitt, A.N. (1979). "A Non-Parametric Approach to the Change-Point Problem". Applied Statistics 28(2): 126-135.

Read, L.K. and R.M. Vogel (2015). "Reliability, Return Periods, and Risk Under Uncertainty," Water Resources Research, 51. DOI: 10.1002/2015WR017089.

Riahi, K, A Grübler, and N Nakicenovic (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol Forecast Soc Chang 74:887–935.

Salas, J. D. and J. Obeysekera (2014). "Revisiting the Concepts of Return Period and Risk for Nonstationary Hydrologic Extreme Events," *Journal of Hydrologic Engineering*, 19(3), 554–568.

Sauer, V., W. Thomas, Jr., V. Stricker, and K. Wilson (1983). "Flood Characteristics of Urban Watersheds in the United States," Water-Supply Paper 2207, U.S. Geological Survey.

Sherman, L. (1932). "Streamflow from Rainfall by Unit-Graph Method" Engineering News-Record 108(14), 501–506.

Smith, SJ and TML Wigley (2006). MultiGas forcing stabilization with minicam. The Energy Journal Special issue #3:373–392.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger (2004). "Changes in Snowmelt Runoff in Western North America Under a "Business as Usual" Climate Change Scenario," Climate Change, Vol. 62, pp. 217-232.

Stoner, A.M.K., K. Hayhoe, X. Yang, and D.J. Wuebbles (2013). "An Asynchronous Regional Regression Model for Statistical Downscaling of Daily Climate Variables," International Journal of Climatology 33(11): 2473-2494.

Swart, R., J. Mitchell, T. Morita and S. Raper, (2002). "Stabilisation Scenarios for Climate Impact Assessment," Global Environmental Change, 12, 155-165.

Task Force on Federal Flood Control Policy (1966). "A Unified National Program for Managing Flood Losses", also referred to as House Document 465 (including the transmittal letter from President Johnson to the Speaker of the House of Representatives), 89th Congress, Second Session, August 10.

Taylor, K.E., Ronald J. Stouffer, and Gerald A. Meehl (2009). "A Summary of the CMIP5 Experiment Design (with updates/corrections made 22 January 2011)," unpublished manuscript retrieved on 6 January 2016 from: http://cmip-pcmdi.llnl.gov/cmip5/guide_to_cmip5.html.

Taylor, K.E., R.J. Stouffer, G.A. Meehl (2012). "An Overview of CMIP5 and the Experiment Design," Bull. Amer. Meteor. Soc., 93, 485¬¬ 498, doi:10.1175/BAMS-D-11-00094.1.

Thomas, W.O., Jr., J.B. Kollat, and J.R. Kasprzyk (2010). "Effects of Climate Change on the National Flood Insurance Program in the United States – Riverine Flooding," Proceedings of the ASCE Watershed Management Conference, August 23-27, 2010, Madison, Wisconsin.

Thompson, D. B. (2006). *The Rational Method, Regional Regression Equations, and Site-Specific Flood-Frequency Relations*, Final Project Report 0–4405–1, TechMRT, Texas Tech University, Lubbock, Texas.

Turner, F.C. (1967). "Evaluation of Flood Hazards – Federally-Financed Highways," Instructional Memorandum 20-1-67, April 26.

UCAR (2016). Information retrieved from http://scied.ucar.edu/longcontent/climate-modeling June 24, 2016, University Corporation for Atmospheric Research.

Unidata (2016). Information retrieved from http://www.unidata.ucar.edu/software/netcdf/ May 16, 2016.

USDOT (2015). U.S. DOT Climate Data Processing Tool: User's Guide. Report prepared under The Gulf Coast Study, Phase 2, Impacts of Climate Change and Variability on Transportation Systems and Infrastructure.

van Vuuren, D.P., B Eickhout, PL Lucas, and MGJ den Elzen (2006). Long-term multi-gas scenarios to stabilise radiative forcing—exploring costs and benefits within an integrated assessment framework. Energ J 27:201–233.

van Vuuren, D.P., MGJ den Elzen, PL Lucas, B Eickhout, BJ Strengers, B van Ruijven, S Wonink, and R Van Houdt (2007). Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Clim Chang 81:119–159.

van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S. J. Smith, and S. K. Rose (2011). The Representative Concentration Pathways: An Overview, Climatic Change 109, 5–31.

Veilleux, A.G., T.A. Cohn, K.M. Flynn, R.R. Mason, Jr., and P.R. Hummel (2014). Estimating Magnitude and Frequency of Floods using the PeakFQ 7.0 Program: U.S. Geological Survey Fact Sheet 2013–3108.

Villarini, G., F. Serinaldi, J.A. Smith, and W.F. Krajewski (2009). “On the Stationarity of Annual Flood Peaks in the Continental United States During the 20th Century”. Water Resources Research 45:W08417. DOI: 10.1029/2008WR007645.

Villarini, G., J.A. Smith, M.L. Baeck, and W.F. Krajewski (2011). ”Examining Flood Frequency Distributions in the Midwest US,” Journal of the American Water Resources Association (JAWRA) 47(3):447-463. DOI: 10.111/j.1752-1688.2011.00540.

Vogel, R.M., C. Yaindl, and M. Walter (2011). “Nonstationarity: Flood Magnification and Recurrence Reduction Factors in the United States”. Journal of the Water Resources Association (JAWRA) 47(3):464-474. DOI: 10.1111/j.1752-1688.2011.00541.

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville (2014). Ch. 2: Our Changing Climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 19-67. doi:10.7930/J0KW5CXT.

Water Resources Council (1978). “Floodplain Management Guidelines For Implementing E.O. 11988,” published in the Federal Register, Vol. 43, No. 29, February 10, 1978, 55 p.

Wayne, G. P. (2013). *The Beginner's Guide to Representative Concentration Pathways, Version 1.0,* http://www.skepticalscience.com/rcp.php?t=2, August.

White, Gilbert Fowler (1945). “Human Adjustment to Floods – A Geographical Approach to the Flood Problem in the United States,” Research Paper 29, The University of Chicago, Dissertation (dissertation completed 1942), pp 179-181.

White, K. (2015). “Projecting Annual Peak Flow Statistics – Food for Thought,” Presentation to the Federal Highway Administration, March 17, 2015.

Wolf, Gregory (2016). “FHWA Information - Disaster losses and other hazard related statistics,” personal communication, FHWA Office of Program Administration, Emergency Relief program, Washington DC, March 30.

Wise, M, K Calvin, A Thomson, L Clarke, B Bond-Lamberty, R Sands, SJ Smith, A Janetos, and J Edmonds (2009). Implications of limiting CO2 concentrations for land use and energy. Science 324:1183–1186.

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Appendix A – Metric System and Conversion Factors

In SI there are seven base units and two supplemental units (Table A.1). Base units uniquely describe a property requiring measurement. One of the most common units in civil engineering is length, with a base unit of meters in SI. Decimal multiples of meter include the kilometer (1000 m), the centimeter (1 m/100) and the millimeter (1 m/1000). The second base unit relevant to highway applications is the kilogram, a measure of mass that is the inertia of an object. For temperature degrees Celsius (°C) has a more common usage than kelvin.

There is a subtle difference between mass and weight. In SI, mass is a base unit, while weight is a derived quantity related to mass and the acceleration of gravity, sometimes referred to as the force of gravity. In SI the unit of mass is the kilogram and the unit of weight/force is the Newton. Table A.2 illustrates the relationship of mass and weight. The unit of time is the same in SI as in the Customary (English) system (seconds). The measurement of temperature is Centigrade. The following equation converts Fahrenheit temperatures to Centigrade, °C = 5/9 (°F - 32).

Derived units are formed by combining base units to express other characteristics. Common derived units in highway drainage engineering include area, volume, velocity, and density. Some derived units have special names (Table A.3).

Table A.4 provides the standard SI prefixes and their definitions. Table A.5 provides useful conversion factors from Customary to SI units. The symbols used in this table for metric (SI) units, including the use of upper and lower case (e.g., kilometer is "km" and a Newton is "N") are the standards that should be followed. The multiplier in the table is given with 4 significant figures; an underline denotes an exact conversion.

Table A.1. Overview of SI.

Unit Category	Unit Measure	Units	Symbol
Base units	Length	meter	m
	Mass	kilogram	kg
	Time	second	s
	temperature	kelvin	K
	electrical current	ampere	A
	luminous intensity	candela	cd
	amount of material	mole	mol
Supplementary units	angles in the plane	radian	rad
	solid angles	steradian	sr

Table A.2. Relationship of mass and weight.

System	Mass	Weight or Force of Gravity	Force
Customary	slug	pound	pound
	pound-mass	pound-force	pound-force
Metric	kilogram	newton	newton

Table A.3. Derived units with special names.

Quantity	Name	Symbol	Expression
Frequency	hertz	Hz	s^{-1}
Force	newton	N	$kg \cdot m/s^2$
Pressure, stress	pascal	Pa	N/m^2
Energy, work, quantity of heat	joule	J	$N \cdot m$
Power, radiant flux	watt	W	J/s
Electric charge, quantity	coulomb	C	$A \cdot s$
Electric potential	volt	V	W/A
Capacitance	farad	F	C/V
Electric resistance	ohm	Ω	V/A
Electric conductance	siemens	S	A/V
Magnetic flux	weber	Wb	$V \cdot s$
Magnetic flux density	tesla	T	Wb/m^2
Inductance	henry	H	Wb/A
Luminous flux	lumen	lm	$cd \cdot sr$
Illuminance	lux	lx	lm/m^2

Table A.4. Prefixes.

Submultiples			Multiples		
Text	Exponent	Symbol	Text	Exponent	Symbol
Deci	10^{-1}	d	deka	10^{1}	da
Centi	10^{-2}	c	hector	10^{2}	h
Milli	10^{-3}	m	kilo	10^{3}	k
Micro	10^{-6}	μ	mega	10^{6}	M
Nano	10^{-9}	n	giga	10^{9}	G
Pica	10^{-12}	p	tera	10^{12}	T
Femto	10^{-15}	f	peta	10^{15}	P
Atto	10^{-18}	a	exa	10^{18}	E
Zepto	10^{-21}	z	zeta	10^{21}	Z
Yocto	10^{-24}	y	yotto	10^{24}	Y

Table A.5. Useful conversion factors.

Quantity	From English Units	To Metric Units	Multiplied by
Length	mile	km	1.609
	yard	m	0.9144
	foot	m	0.3048
	inch	mm	25.4
Area	square mile	km^2	2.590
	acre	m^2	4047
	acre	hectare	0.4047
	square yard	m^2	0.8361
	square foot	m^2	0.092 90
	square inch	mm^2	645.2
Volume	acre foot	m^3	1 233
	cubic yard	m^3	0.7646
	cubic foot	m^3	0.028 32
	cubic foot	L (1000 cm^3)	28.32
	100 board feet	m^3	0.2360
	gallon	L (1000 cm^3)	3.785
	cubic inch	cm^3	16.39
Mass	lb	kg	0.4536
	kip (1000 lb)	metric ton (1000 kg)	0.4536
Mass/unit length	plf	kg/m	1.488
Mass/unit area	psf	kg/m^2	4.882
Mass density	pcf	kg/m^3	16.02
Force	lb	N	4.448
	kip	kN	4.448
Force/unit length	plf	N/m	14.59
	klf	kN/m	14.59
Pressure, stress, modulus of elasticity	psf	Pa	47.88
	ksf	kPa	47.88
	psi	kPa	6.895
	ksi	MPa	6.895
Bending moment, torque, moment of force	ft-lb	N A m	1.356
	ft-kip	kN A m	1.356
Moment of mass	lb · ft	kg · m	0.1383
Moment of inertia	lb · ft^2	kg · m^2	0.042 14
Second moment of area	In^4	mm^4	416 200
Section modulus	In^3	mm^3	16 390
Power	ton (refrig)	kW	3.517
	Btu/s	kW	1.054
	hp (electric)	W	745.7
	Btu/h	W	0.2931
Volume rate of flow	ft^3/s	m^3/s	0.028 32
	cfm	m^3/s	0.000 471 9
	cfm	L/s	0.4719
	mgd	m^3/s	0.0438
Velocity, speed	ft/s	m/s	0.3048
Acceleration	f/s^2	m/s^2	0.3408
Momentum	lb · ft/sec	kg · m/s	0.1383
Angular momentum	lb · ft^2/s	kg · m^2/s	0.042 14
Plane angle	Degree	rad	0.017 45
		mrad	17.45

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Appendix B – 23 CFR 650 (A)

PART 650 - BRIDGES, STRUCTURES, AND HYDRAULICS

Subpart A - Location and Hydraulic Design of Encroachments on Flood Plains

Sec.

Authority:23 U.S.C. 109 (a) and (h), 144, 151, 315, and 319; 23 CFR 1.32; 49 CFR 1.48(b), E.O. 11988 (3 CFR, 1977 Comp. p. 117); Department of Transportation Order 5650.2 dated April 23, 1979 (44 FR 24678); section 161 of Public Law 97-424, 96 Stat. 2097, 3135; section 4(b) of Public Law 97-134,95 Stat. 1699; and 33 U.S.C. 401, 491 et seq., 511 et seq.; and section 1057 of Public Law 102-240, 105 Stat. 2002.

[59 FR 37935, July 26, 1994]

Source:44 FR 67580, Nov. 26, 1979, unless otherwise noted.

Sec. 650.101 Purpose.

To prescribe Federal Highway Administration (FHWA) policies and procedures for the location and hydraulic design of highway encroachments on flood plains, including direct Federal highway projects administered by the FHWA.

Sec. 650.103 Policy.

It is the policy of the FHWA:

(a) To encourage a broad and unified effort to prevent uneconomic, hazardous or incompatible use and development of the Nation's flood plains,

(b) To avoid longitudinal encroachments, where practicable,

(c) To avoid significant encroachments, where practicable,

(d) To minimize impacts of highway agency actions which adversely affect base flood plains,

(e) To restore and preserve the natural and beneficial flood-plain values that are adversely impacted by highway agency actions,

(f) To avoid support of incompatible flood-plain development,

(g) To be consistent with the intent of the Standards and Criteria of the National Flood Insurance Program, where appropriate, and

(h) To incorporate "A Unified National Program for Floodplain Management" of the Water Resources Council into FHWA procedures.

Sec. 650.105 Definitions.

(a) "Action" shall mean any highway construction, reconstruction, rehabilitation, repair, or improvement undertaken with Federal or Federal-aid highway funds or FHWA approval.

(b) "Base flood" shall mean the flood or tide having a 1 percent chance of being exceeded in any given year.

(c) "Base flood plain" shall mean the area subject to flooding by the base flood.

(d) "Design Flood" shall mean the peak discharge, volume if appropriate, stage or wave crest elevation of the flood associated with the probability of exceedance selected for the design of a highway encroachment. By definition, the highway will not be inundated from the stage of the design flood.

(e) "Encroachment" shall mean an action within the limits of the base flood plain.

(f) "Floodproof" shall mean to design and construct individual buildings, facilities, and their sites to protect against structural failure, to keep water out or to reduce the effects of water entry.

(g) "Freeboard" shall mean the vertical clearance of the lowest structural member of the bridge superstructure above the water surface elevation of the overtopping flood.

(h) "Minimize" shall mean to reduce to the smallest practicable amount or degree.

(i) "Natural and beneficial flood-plain values" shall include but are not limited to fish, wildlife, plants, open space, natural beauty, scientific study, outdoor recreation, agriculture, aquaculture, forestry, natural moderation of floods, water quality maintenance, and groundwater recharge.

(j) "Overtopping flood" shall mean the flood described by the probability of exceedance and water surface elevation at which flow occurs over the highway, over the watershed divide, or through structure(s) provided for emergency relief.

(k) "Practicable" shall mean capable of being done within reasonable natural, social, or economic constraints.

(l) "Preserve" shall mean to avoid modification to the functions of the natural flood-plain environment or to maintain it as closely as practicable in its natural state.

(m) "Regulatory floodway" shall mean the flood-plain area that is reserved in an open manner by Federal, State or local requirements, i.e., unconfined or unobstructed either horizontally or vertically, to provide for the discharge of the base flood so that the cumulative increase in water surface elevation is no more than a designated amount (not to exceed 1 foot as established by the Federal Emergency Management Agency (FEMA) for administering the National Flood Insurance Program).

(n) "Restore" shall mean to reestablish a setting or environment in which the functions of the natural and beneficial flood-plain values adversely impacted by the highway agency action can again operate.

(o) "Risk" shall mean the consequences associated with the probability of flooding attributable to an encroachment. It shall include the potential for property loss and hazard to life during the service life of the highway.

(p) "Risk analysis" shall mean an economic comparison of design alternatives using expected total costs (construction costs plus risk costs) to determine the alternative with the least total expected cost to the public. It shall include probable flood-related costs during the service life of the facility for highway operation, maintenance, and repair, for highway-aggravated flood damage to other property, and for additional or interrupted highway travel.

(q) "Significant encroachment" shall mean a highway encroachment and any direct support of likely base flood-plain development that would involve one or more of the following construction-or flood-related impacts:

(1) A significant potential for interruption or termination of a transportation facility which is needed for emergency vehicles or provides a community's only evacuation route.

(2) A significant risk, or

(3) A significant adverse impact on natural and beneficial flood-plain values.

(r) "Support base flood-plain development" shall mean to encourage, allow, serve, or otherwise facilitate additional base flood-plain development. Direct support results from an encroachment, while indirect support results from an action out of the base flood plain.

Sec. 650.107 Applicability.

(a) The provisions of this regulation shall apply to all encroachments and to all actions which affect base flood plains, except for repairs made with emergency funds (23 CFR Part 668) during or immediately following a disaster.

(b) The provisions of this regulation shall not apply to or alter approvals or authorizations which were given by FHWA pursuant to regulations or directives in effect before the effective date of this regulation.

Sec. 650.109 Public involvement.

Procedures which have been established to meet the public involvement requirements of 23 CFR Part 771 shall be used to provide opportunity for early public review and comment on alternatives which contain encroachments.

[53 FR 11065, Apr. 5, 1988]

Sec. 650.111 Location hydraulic studies.

(a) National Flood Insurance Program (NFIP) maps or information developed by the highway agency, if NFIP maps are not available, shall be used to determine whether a highway location alternative will include an encroachment.

(b) Location studies shall include evaluation and discussion of the practicability of alternatives to any longitudinal encroachments.

(c) Location studies shall include discussion of the following items, commensurate with the significance of the risk or environmental impact, for all alternatives containing encroachments and for those actions which would support base flood-plain development:

(1) The risks associated with implementation of the action,

(2) The impacts on natural and beneficial flood-plain values,

(3) The support of probable incompatible flood-plain development,

(4) The measures to minimize flood-plain impacts associated with the action, and

(5) The measures to restore and preserve the natural and beneficial flood-plain values impacted by the action.

(d) Location studies shall include evaluation and discussion of the practicability of alternatives to any significant encroachments or any support of incompatible flood-plain development.

(e) The studies required by Sec. 650.111 (c) and (d) shall be summarized in environmental review documents prepared pursuant to 23 CFR Part 771.

(f) Local, State, and Federal water resources and flood-plain management agencies should be consulted to determine if the proposed highway action is consistent with existing watershed and flood-plain management programs and to obtain current information on development and proposed actions in the affected watersheds.

Sec. 650.113 Only practicable alternative finding.

(a) A proposed action which includes a significant encroachment shall not be approved unless the FHWA finds that the proposed significant encroachment is the only practicable alternative. This finding shall be included in the final environmental document (final environmental impact statement or finding of no significant impact) and shall be supported by the following information:

(1) The reasons why the proposed action must be located in the flood plain,

(2) The alternatives considered and why they were not practicable, and

(3) A statement indicating whether the action conforms to applicable State or local flood-plain protection standards.

[44 FR 67580, Nov. 26, 1979, as amended at 48 FR 29274, June 24, 1983]

Sec. 650.115 Design standards.

(a) The design selected for an encroachment shall be supported by analyses of design alternatives with consideration given to capital costs and risks, and to other economic, engineering, social and environmental concerns.

(1) Consideration of capital costs and risks shall include, as appropriate, a risk analysis or assessment which includes:

(i) The overtopping flood or the base flood, whichever is greater, or

(ii) The greatest flood which must flow through the highway drainage structure(s), where overtopping is not practicable. The greatest flood used in the analysis is subject to state-of-the-art capability to estimate the exceedance probability.

(2) The design flood for encroachments by through lanes of Interstate highways shall not be less than the flood with a 2 percent chance of being exceeded in any given year. No minimum design flood is specified for Interstate highway ramps and frontage roads or for other highways.

(3) Freeboard shall be provided, where practicable, to protect bridge structures from debris- and scour-related failure.

(4) The effect of existing flood control channels, levees, and reservoirs shall be considered in estimating the peak discharge and stage for all floods considered in the design.

(5) The design of encroachments shall be consistent with standards established by the FEMA, State, and local governmental agencies for the administration of the National Flood Insurance Program for:

(i) All direct Federal highway actions, unless the standards are demonstrably inappropriate, and

(ii) Federal-aid highway actions where a regulatory floodway has been designated or where studies are underway to establish a regulatory floodway.

(b) Rest area buildings and related water supply and waste treatment facilities shall be located outside the base flood plain, where practicable. Rest area buildings which are located on the base flood plain shall be floodproofed against damage from the base flood.

(c) Where highway fills are to be used as dams to permanently impound water more than 50 acre-feet ($6.17 X 10^4$ cubic metres) in volume or 25 feet (7.6 metres) deep, the hydrologic, hydraulic, and structural design of the fill and appurtenant spillways shall have the approval of the State or Federal agency responsible for the safety of dams or like structures within the State, prior to authorization by the Division Administrator to advertise for bids for construction.

Sec. 650.117 Content of design studies.

(a) The detail of studies shall be commensurate with the risk associated with the encroachment and with other economic, engineering, social or environmental concerns.

(b) Studies by highway agencies shall contain:

(1) The hydrologic and hydraulic data and design computations,

(2) The analysis required by Sec. 650.115(a), and

(3) For proposed direct Federal highway actions, the reasons, when applicable, why FEMA criteria (44 CFR 60.3, formerly 24 CFR 1910.3) are demonstrably inappropriate.

(c) For encroachment locations, project plans shall show:

(1) The magnitude, approximate probability of exceedance and, at appropriate locations, the water surface elevations associated with the overtopping flood or the flood of Sec. 650.115(a)(1) (ii), and

(2) The magnitude and water surface elevation of the base flood, if larger than the overtopping flood.

Appendix C – FHWA Order 5520

The full text of FHWA Order 5520 is provided on the following pages.

Order

U.S. DEPARTMENT OF TRANSPORTATION

1.1. Federal Highway
1.2. Administration

Subject: **Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events**

Classification Code	Date	Office of Primary Interest
5520	December 15, 2014	HEP/HIF/FLH

1. **What is the purpose of this directive?** The purpose of this directive is to establish the Federal Highway Administration (FHWA) policy on preparedness and resilience to climate change and extreme weather events. This directive further serves to implement relevant provisions of title 23 of the United States Code (U.S.C), to comply with Executive Order 13653, Preparing the United States for the Impacts of Climate Change (EO 13653), dated November 1, 2013, and further the U.S. Department of Transportation (DOT) Policy Statement on Climate Change Adaptation.

2. **Does this directive cancel an existing FHWA directive?** No. This is a new FHWA directive.

3. ***What is the background of this directive?***

   a. Climate change and extreme weather events present significant and growing risks to the safety, reliability, effectiveness, and sustainability of the Nation's transportation infrastructure and operations.

   b. The impacts of a changing climate (such as higher temperatures, sea-level rise, and changes in seasonal precipitation and the intensity of rain events) and extreme weather events are affecting the lifecycle of transportation systems and are expected to intensify. For example, sea level rise coupled with storm surges can inundate coastal roads that would not have inundated in the past, necessitate more emergency evacuations, and require costly, and sometimes recurring, repairs to damaged infrastructure. Inland flooding from unusually heavy downpours can disrupt traffic, damage culverts, and reduce service life. High heat can degrade materials, resulting in shorter replacement cycles and higher maintenance costs.

c. While transportation infrastructure is designed to handle a broad range of impacts based on historic climate, preparing for climate change and extreme weather events is critical to protecting the integrity of the transportation system and the sound investment of taxpayer dollars.

4. ***What authorities govern this directive?***

a. 23 U.S.C. § 109. Federally funded highway restoration, rehabilitation or resurfacing projects shall be done in such a way as to "preserve and extend the service life of highways and enhance highway safety." Designs for new or reconstructed facilities on the National Highway System may account for the "constructed and natural environment of the area."

b. 23 U.S.C. § 116. Preventive maintenance is a "cost-effective means of extending the useful life of a Federal-aid highway."

c. 23 U.S.C. § 119(d)(2)(B) and (C). Allows FHWA to provide Federal aid funds for "... construction, replacement ..., rehabilitation, preservation, and protection (including ... protection against extreme events) of bridges on the National Highway System" and "… construction, replacement ..., rehabilitation, preservation, and protection (including ... protection against extreme events) of tunnels on the National Highway System."

d. 23 U.S.C. § 133(b)(2). Allows FHWA to provide Federal-aid funds for "... replacement ..., rehabilitation, preservation, protection (including ... protection against extreme events) ... of bridges (and approaches to bridges and other elevated structures) and tunnels on public roads of all functional classifications, including any such construction or reconstruction necessary to accommodate other transportation modes."

e. 23 U.S.C. § 134 (a)(1). States that "It is in the national interest... to encourage and promote the safe and efficient management, operation, and development of surface transportation systems...within and between States and urbanized areas..."

f. 23 U.S.C. § 150(b). Identifies that it is a national transportation goal to maintain the highway infrastructure in a state of good repair (Infrastructure Condition) and improve the efficiency of the surface transportation system (System Reliability).

g. 23 U.S.C. § 503(b)(3)(B)(viii). Requires that "… the Secretary shall carry out research and development activities ... to study vulnerabilities of the transportation system to ... extreme events and methods to reduce those vulnerabilities."

h. Executive Order (EO) 13653. Preparing the United States for the Impacts of Climate Change (EO 13653). dated November 1. 2013. Requires Federal agencies to prepare the Nation for the impacts of climate change by undertaking actions to enhance climate preparedness and resilience. In doing so, agencies should promote: (1) engaged and strong partnerships and information sharing at all levels of government; (2) risk-informed decision making and the tools to facilitate it, (3) adaptive learning, in which experiences serve as opportunities to inform and adjust future actions, and (4) preparedness planning.

i. Executive Order 13514. Federal Leadership in Environmental. Energy. and Economic Performance (EO 13514). dated October 5. 2009. Requires Federal agencies to develop Agency Adaptation Plans and submit them to the Council on Environmental Quality and Office of Management and Budget for review. These plans are to evaluate the most significant climate change related risks to, and vulnerabilities in, agency operations and missions in both the short and long term, and outline actions that agencies will take to manage these risks and vulnerabilities.

j. U.S. DOT Policy Statement on Climate Change Adaptation. Provides guiding principles on climate change adaptation.

5. What is the scope of this directive? This Order applies to FHWA's programs, policies, and activities related to preparedness and resilience to climate change and extreme weather events (see paragraph 6. Definitions, a through f).

6. What definitions are used in this directive?

a. **Climate Change.** Climate change refers to any significant change in the measures of climate lasting for an extended period of time. Climate change includes major variations in temperature, precipitation, or wind patterns, among other environmental conditions, that occur over several decades or longer. Changes in climate may manifest as a rise in sea level, as well as increase the frequency and magnitude of extreme weather events now and in the future.

b. **Extreme Weather Events.** Extreme weather events can include significant anomalies in temperature, precipitation and winds and can manifest as heavy precipitation and flooding, heatwaves, drought, wildfires and windstorms (including tornadoes and tropical storms). Consequences of extreme weather events can include safety concerns, damage, destruction, and/or economic loss. Climate change can also cause or influence extreme weather events.

c. **Extreme Events.** For the purposes of this directive, the term "extreme events" refers to risks posed by climate change and extreme weather events. The definition does not apply to other uses of the term nor include consideration of risks to the transportation system from other natural hazards, accidents, or other human induced disruptions.[1]

[1] Provisions in 23 U.S.C. §§ 119(d)(2)(B) and (C), 133(b)(2), and 503(b)(3)(B)(vi ii) address extreme events separately from measures to address seismic and security concerns.

d. **Preparedness.** Preparedness means actions taken to plan, organize, equip, train, and exercise to build, apply, and sustain the capabilities necessary to prevent, protect against, ameliorate the effects of, respond to, and recover from climate change related damages to life, health, property, livelihoods, ecosystems, and national security.

e. **Resilience.** Resilience or resiliency is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.

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

7. What is the FHWA's policy concerning climate change and extreme weather event preparedness and resilience?

a. It is FHWA's policy to strive to identify the risks of climate change and extreme weather events to current and planned transportation systems. The FHWA will work to integrate consideration of these risks into its planning, operations, policies and programs in order to promote preparedness and resilience; safeguard Federal investments; and ensure the safety, reliability, and sustainability of the Nation's transportation systems.

b. Several provisions in title 23 address the need to consider the effects of extreme events in the delivery of programs and projects (23 U.S.C. §§ 119(d)(2)(B) and (C), 133(b)(2), and 503(b)(3)(B)(viii)). Under EO 13653, each Federal agency must work to prepare the Nation for the impacts of climate change by undertaking actions to enhance climate preparedness and resilience. The FHWA will implement these relevant provisions in title 23, EO 13653, EO 13514, and subsequent laws, regulations and policies. The FHWA will also implement the principles of the DOT Policy Statement on Climate Change Adaptation by incorporating consideration of climate change and extreme weather event preparedness and resilience in all FHWA programs, policies, and activities within the framework of existing laws, regulations, and guidance.

c. Following the policy set forth in this directive, FHWA managers and staff shall ensure that FHWA programs, policies, and activities for which they are responsible integrate consideration of climate change and extreme weather event impacts and adaptation into its planning, operations, policies and programs, in order to promote climate change and extreme weather event preparedness and resilience. Proactive management involves developing engineering solutions, operations and maintenance strategies, asset management plans and transportation programs that address risk and promote resilience at both the project and systems levels.

8. **What are the FHWA's responsibilities?** The FHWA will integrate consideration of the risks of climate change and extreme weather event impacts and adaptation responses, into the delivery and stewardship of the Federal-aid and Federal Lands Highway programs by:

a. Identifying and removing administrative, regulatory, and policy barriers that discourage climate change and extreme weather event preparedness and resiliency or unintentionally increase the vulnerability of transportation systems to these risks.

b. Encouraging State departments of transportation (DOT), metropolitan planning organizations (MPO), Federal land management agencies (FLMAs), tribal governments, and others to develop, prioritize, implement and evaluate risk- based and cost-effective strategies to minimize climate and extreme weather risks and protect critical infrastructure using the best available science, technology and information.

c. Developing and providing technical assistance, research, and outreach, and encouraging the development and use of transportation-specific vulnerability assessment and adaptation tools.

d. Clarifying and informing State DOTs, MPOs, FLMAs, tribal governments, and others of existing funding eligibilities to support resiliency and adaptation in the delivery of title 23 programs.

e. Developing research and tools, providing technical assistance, and building partnerships with State DOTs and MPOs, particularly in development and analysis of adaptation, preparedness, and resiliency options.

f. Encouraging the consideration of climate change and extreme weather event risks, preparedness and resiliency in the delivery of programs, such as in the risk-based asset management plans State DOTs are required to develop under MAP-21.

g. Updating planning, engineering, and operations guidance to include consideration of climate change and extreme weather event resilience.

h. Reporting on progress through the US DOT Adaptation Plan and internal FHWA strategic planning activities.

9. **Where can I obtain additional guidance?** For more information or additional guidance related to climate change and extreme weather event preparedness and resilience, please see the FHWA Climate Change web site.

Gregory G. Nadeau
Acting Administrator

Appendix D – Executive Order 13690

The full text of Executive Order 13690 is provided in the following pages.

EXECUTIVE ORDER 13690

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Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input

By the authority vested in me as President by the Constitution and the laws of the United States of America, and in order to improve the Nation's resilience to current and future flood risk, I hereby direct the following:

Section 1. *Policy.* It is the policy of the United States to improve the resilience of communities and Federal assets against the impacts of flooding. These impacts are anticipated to increase over time due to the effects of climate change and other threats. Losses caused by flooding affect the environment, our economic prosperity, and public health and safety, each of which affects our national security.

The Federal Government must take action, informed by the best-available and actionable science, to improve the Nation's preparedness and resilience against flooding. Executive Order 11988 of May 24, 1977 (Floodplain Management), requires executive departments and agencies (agencies) to avoid, to the extent possible, the long- and short-term adverse impacts associated with the occupancy and modification of floodplains and to avoid direct or indirect support of floodplain development wherever there is a practicable alternative. The Federal Government has developed processes for evaluating the impacts of Federal actions in or affecting floodplains to implement Executive Order 11988.

As part of a national policy on resilience and risk reduction consistent with my *Climate Action Plan*, the National Security Council staff coordinated an interagency effort to create a new flood risk reduction standard for federally funded projects. The views of Governors, mayors, and other stakeholders were solicited and considered as efforts were made to establish a new flood risk reduction standard for federally funded projects. The result of these efforts is the Federal Flood Risk Management Standard (Standard), a flexible framework to increase resilience against flooding and help preserve the natural values of floodplains. Incorporating this Standard will ensure that agencies expand management from the current base flood level to a higher vertical elevation and corresponding horizontal floodplain to address current and future flood risk and ensure that projects funded with taxpayer dollars last as long as intended.

This order establishes the Standard and sets forth a process for further solicitation and consideration of public input, including from Governors, mayors, and other stakeholders, prior to implementation of the Standard.

Sec. 2. *Amendments to Executive Order 11988.* Executive Order 11988 is amended as follows:

(a) Section 2 is amended by inserting ", to the extent permitted by law" after "as follows".

(b) Section 2(a)(1) is amended by striking "This Determination shall be made according to a Department of Housing and Urban Development (HUD) floodplain map or a more detailed map of an area, if available. If such maps are not available, the agency shall make a determination of the location of the floodplain based on the best-available information. The Water Resources Council shall issue guidance on this information not later than October 1, 1977" and inserting in lieu thereof "To determine whether the action is located in a floodplain, the agency shall use one of the approaches in Section 6(c) of this Order based on the best-available information and the Federal Emergency Management Agency's effective Flood Insurance Rate Map".

(c) Section 2(a)(2) is amended by inserting the following sentence after the first sentence: "Where possible, an agency shall use natural systems, ecosystem processes, and nature-based approaches when developing alternatives for consideration.".

(d) Section 2(d) is amended by striking "Director" and inserting "Administrator" in lieu thereof.

(e) Section 3(a) is amended by inserting the following sentence after the first sentence: "The regulations and procedures must also be consistent with the Federal Flood Risk Management Standard (FFRMS).".

(f) Section 3(a) is further amended by inserting "and FFRMS" after "Flood Insurance Program".

(g) Section 3(b) is amended by striking "base flood level" and inserting "elevation of the floodplain as defined in Section 6(c) of this Order" in lieu thereof.

(h) Section 4 is revised to read as follows: "In addition to any responsibilities under this Order and Sections 102, 202, and 205 of the Flood Disaster Protection Act of 1973, as amended (42 U.S.C. 4012a, 4106, and 4128), agencies which guarantee, approve, regulate, or insure any financial transaction which is related to an area located in an area subject to the base flood shall, prior to completing action on such transaction, inform any private parties participating in the transaction of the hazards of locating structures in the area subject to the base flood.”.

(i) Section 6(c) is amended by striking “, including at a minimum, that area subject to a one percent or greater chance of flooding in any given year” and inserting in lieu thereof: “. The floodplain shall be established using one of the following approaches:

“(1) Unless an exception is made under paragraph (2), the floodplain shall be:

“(i) the elevation and flood hazard area that result from using a climate-informed science approach that uses the best-available, actionable hydrologic and hydraulic data and methods that integrate current and future changes in flooding based on climate science. This approach will also include an emphasis on whether the action is a critical action as one of the factors to be considered when conducting the analysis;

“(ii) the elevation and flood hazard area that result from using the freeboard value, reached by adding an additional 2 feet to the base flood elevation for non-critical actions and by adding an additional 3 feet to the base flood elevation for critical actions;

“(iii) the area subject to flooding by the 0.2 percent annual chance flood; or

“(iv) the elevation and flood hazard area that result from using any other method identified in an update to the FFRMS.

“(2) The head of an agency may except an agency action from paragraph (1) where it is in the interest of national security, where the agency action is an emergency action, where application to a Federal facility or structure is demonstrably inappropriate, or where the agency action is a mission-critical requirement related to a national security interest or an emergency action. When an agency action is excepted from paragraph (1) because it is in the interest of national security, it is an emergency action, or it is a mission-critical requirement related to a national security interest or an emergency action, the agency head shall rely on the area of land subject to the base flood”.

(j) Section 6 is further amended by adding the following new subsection (d) at the end: “(d) The term ‘critical action’ shall mean any activity for which even a slight chance of flooding would be too great.”.

(k) Section 8 is revised to read as follows: “Nothing in this Order shall apply to assistance provided for emergency work essential to save lives and protect property and public health and safety, performed pursuant to Sections 403 and 502 of the Robert T. Stafford Disaster Relief and Emergency Assistance Act of 1988 (42 U.S.C. 5170b and 5192).”.

Sec. 3. *Agency Action.*

(a) Prior to any action to implement the Standard, additional input from stakeholders shall be solicited and considered. To carry out this process:

(i) the Federal Emergency Management Agency, on behalf of the Mitigation Framework Leadership Group, shall publish for public comment draft amended Floodplain Management Guidelines for Implementing Executive Order 11988 (Guidelines) to provide guidance to agencies on the implementation of Executive Order 11988, as amended, consistent with the Standard;

(ii) during the comment period, the Mitigation Framework Leadership Group shall host public meetings with stakeholders to solicit input; and

(iii) after the comment period closes, and based on the comments received on the draft Guidelines during the comment period, in accordance with subsections (a)(i) and(ii) of this section, the Mitigation Framework Leadership Group shall provide recommendations to the Water Resources Council.

(b) After additional input from stakeholders has been solicited and considered as set forth in subsections (a)(i) and (ii) of this section and after consideration of the recommendations made by the Mitigation Framework Leadership Group pursuant to subsection (a)(iii) of this section, the Water Resources Council shall issue amended Guidelines to provide guidance to agencies on the implementation of Executive Order 11988, as amended, consistent with the Standard.

(c) To the extent permitted by law, each agency shall, in consultation with the Water Resources Council, Federal Interagency Floodplain Management Task Force, Federal Emergency Management Agency, and Council on Environmental Quality, issue or amend existing regulations and procedures to comply with this order, and update those regulations and procedures as warranted. Within 30 days of the closing of the public comment period for the draft amendments to the Guidelines as described in subsection (a) of this section, each agency shall submit an implementation plan to the National Security Council staff that contains milestones and a timeline for implementation of this order and the Standard, by the agency as it applies to the agency's processes and mission. Agencies shall not issue or amend existing regulations and procedures pursuant to this subsection until after the

Water Resources Council has issued amended Guidelines pursuant to subsection (b) of this order.

Sec. 4. *Reassessment.*

(a) The Water Resources Council shall issue any further amendments to the Guidelines as warranted.

(b) The Mitigation Framework Leadership Group in consultation with the Federal Interagency Floodplain Management Task Force shall reassess the Standard annually, after seeking stakeholder input, and provide recommendations to the Water Resources Council to update the Standard if warranted based on accurate and actionable science that takes into account changes to climate and other changes in flood risk. The Water Resources Council shall issue an update to the Standard at least every 5 years.

Sec. 5. *General Provisions.*

(a) Nothing in this order shall be construed to impair or otherwise affect:

(i) the authority granted by law to an executive department, agency, or the head thereof; or

(ii) the functions of the Director of the Office of Management and Budget relating to budgetary, administrative, or legislative proposals.

(b) This order shall be implemented consistent with applicable law and subject to the availability of appropriations.

(c) This order is not intended to, and does not, create any right or benefit, substantive or procedural, enforceable at law or in equity by any party against the United States, its departments, agencies, or entities, its officers, employees, or agents, or any other person.

(d) The Water Resources Council shall carry out its responsibilities under this order in consultation with the Mitigation Framework Leadership Group.

THE WHITE HOUSE,

January 30, 2015.