# Federal Flood Risk Management Standard Climate-Informed Science Approach (CISA) State of the Science Report

A Report by the

**Federal Flood Risk Management Standard (FFRMS) Science Subgroup of the**

**Flood Resilience Interagency Working Group**

of the

**NATIONAL CLIMATE TASK FORCE**

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## About this Document

Executive Order (EO) 13690 on *Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input* (2015) establishes a Federal Flood Risk Management Standard (FFRMS) to ensure that agencies take actions to enhance the Nation's resilience to current and future flooding. EO 13690 modernizes EO 11988, *Floodplain Management*, by expanding the floodplain area to be considered for projects funded with taxpayer dollars (Federally-funded projects) to a higher vertical elevation and corresponding horizontal floodplain area (FFRMS floodplain) that would address current and future flood risk due to the effects of climate change and other future changes. EO 13690 also encourages climate-conscious resilient design if there are no practicable locations outside the FFRMS floodplain. To identify the FFRMS floodplain, EO 13690 requires agencies to use a Climate Informed Science Approach, a Freeboard Value Approach, a 0.2-Percent-Annual-Chance Value Approach, or the elevation and flood hazard area that result from using any other method identified in an update of the FFRMS.

This report provides a review and update of the best-available, actionable science that can support application of the Climate-Informed Science Approach (CISA), reflecting science and technology advancements made since EO 13690 was issued in 2015. This report does not update the Federal Flood Risk Management Standard (FFRMS) or amend the 2015 guidelines for implementing EOs 11988 (*Floodplain Management*) and 13690. The report is intended to assist Federal agencies in applying CISA based on the latest knowledge and actionable science. This report also identifies opportunities for further research and collaboration for assessing and addressing flood risks being influenced by climate change. While the report is primarily intended for Federal agency staff and partners applying FFRMS, other stakeholders may find this information useful in advancing floodplain science and management. This work was completed under the auspices of the National Climate Task Force, including the subordinate bodies listed below, and in consultation with agencies that participate in the Federal Interagency Floodplain Management Task Force (FIFM-TF).

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Launched in August 2021, the Flood Resilience Interagency Working Group (IWG) under the National Climate Task Force is part of the Administration's whole-of-government approach to building flood resilience. It was formed by the White House Climate Policy Office in response to EO 14030 on Climate-Related Financial Risk, which reinstated EO 13690 and, in doing so, reestablished the FFRMS. The Flood Resilience IWG is co-led by the Council on Environmental Quality (CEQ), the Office of Management and Budget (OMB), and the Department of Homeland Security (DHS) Federal Emergency Management Agency (FEMA) to coordinate Federal agencies' implementation of FFRMS and other flood priorities.

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## Federal Flood Risk Management Standard (FFRMS) Science Subgroup

In October 2021, the Flood Resilience IWG convened an FFRMS Science Subgroup to review and update the best-available, actionable science and guidance underpinning the standard, and to facilitate development and delivery of science-based implementation resources that support consistent application of the standard by Federal agencies and non-Federal partners.

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## Abbreviations and Acronyms

| | |
|---|---|
| **0.2PFA** | 0.2-Percent Flood Approach |
| **ADCIRC** | Advanced Circulation |
| **AEP** | Annual exceedance probability |
| **ASFPM** | Association of State Floodplain Managers |
| **BFE** | Base Flood Elevation |
| **CEQ** | Council on Environmental Quality |
| **CISA** | Climate-Informed Science Approach |
| **CMIP** | Coupled Model Intercomparison Project |
| **CONUS** | Continental U.S. |
| **CoP** | Community of Practice |
| **DCHP** | Downscaled CMIP Climate and Hydrology Projections |
| **DEM** | Digital Elevation Model |
| **DFIRM** | Digital Flood Insurance Rate Maps |
| **DHS** | Department of Homeland Security |
| **DOD** | Department of Defense |
| **DOE** | Department of Energy |
| **DOT** | Department of Transportation |
| **EDA** | Economic Development Administration |
| **EO** | Executive Order |
| **EM** | Engineer Manual |
| **EPA** | Environmental Protection Agency |
| **ER** | Engineer Regulation |
| **ERDC-CHL** | (U.S Army) Engineer Research and Development Center's Coastal and Hydraulics Laboratory |
| **FEH** | Fluvial erosion hazard |
| **FEMA** | Federal Emergency Management Agency |
| **FFRD** | The Future of Flood Risk Data |
| **FFRMS** | Federal Flood Risk Management Standard |
| **FHWA** | Federal Highways Administration |
| **FIFM-TF** | Federal Interagency Floodplain Management Task Force |
| **FIRM** | Flood Insurance Rate Map |
| **FVA** | Freeboard Value Approach |

| | |
|---|---|
| **FY** | Fiscal Year |
| **GCM** | Global Climate Model |
| **GHG** | Greenhouse gas |
| **GIS** | Geographic information system |
| **GSA** | General Services Administration |
| **H&H** | Hydrology and hydraulics |
| **HDSC** | Hydrometeorological Design Studies Center |
| **HEC-RAS** | USACE Hydrologic Engineering Center's River Analysis System |
| **HHS** | Department of Health and Human Services |
| **HUD** | Department of Housing and Urban Development |
| **IDF** | Intensity-duration-frequency |
| **InSAR** | Interferometric Synthetic Aperture Radar |
| **iRIC** | International River Interface Cooperative |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **IWG** | Interagency Working Group |
| **JPM-OS** | Joint Probability Method with Optimal Sampling |
| **LiDAR** | Light Detection and Ranging |
| **LOCA** | Localized Constructed Analog |
| **LTCE** | Long-term coastal erosion |
| **MSL** | Mean sea level |
| **NACCS** | North Atlantic Coast Comprehensive Study |
| **NASA** | National Aeronautics and Space Administration |
| **NCA** | National Climate Assessment |
| **NFIP** | National Flood Insurance Program |
| **NIST** | National Institute of Standards and Technology |
| **NOAA** | National Oceanic and Atmospheric Administration |
| **NPS** | National Park Service |
| **NSRS** | National Spatial Reference System |
| **NWM** | National Water Model |
| **NWS** | National Weather Service |
| **OMB** | Office of Management and Budget |
| **OSTP** | Office of Science and Technology Policy |
| **RCP** | Representative Concentration Pathway |

| | |
|---|---|
| **RSL** | Relative sea level |
| **SBA** | Small Business Administration |
| **SCHISM** | Semi-Implicit Cross-Scale Hydroscience Integrated System Model |
| **SLR** | Sea-level rise |
| **SSP** | Socioeconomic pathway |
| **TMAC** | FEMA Technical Mapping Advisory Council |
| **U.S.** | United States |
| **USACE** | U.S. Army Corps of Engineers |
| **USBR** | U.S. Bureau of Reclamation |
| **USDA** | U.S. Department of Agriculture |
| **USGCRP** | U.S. Global Change Research Program |
| **USGS** | U.S. Geological Survey |
| **VLM** | Vertical Land Motion |
| **WRC** | Water Resources Council |

# Executive Summary

This Climate-Informed Science Approach (CISA) State of the Science report reviews and updates the science to be considered when implementing the Federal Flood Risk Management Standard (FFRMS) under Executive Order (EO) 13690, *Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input*. On October 8, 2015, the Mitigation Framework Leadership Group released the *Guidelines for Implementing Executive Order 11988, Floodplain Management, and Executive Order 13690, Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input* (hereinafter, 2015 IG).[1] This report complements and augments Appendix H of the 2015 IG (hereinafter, 2015 CISA Appendix[2]), which encourages a risk-based approach to identifying the CISA for floodplain identification, and describes the state of the science for a more complete suite of flooding types (coastal, riverine, pluvial, and compound). As with the 2015 CISA Appendix, this report is intended to serve as non-prescriptive, scientific and engineering guidance that Federal agencies, their non-Federal partners, and other entities can use in determining future flood hazards under the FFRMS' CISA.

The FFRMS includes four approaches for determining a future flood elevation for Federally-funded projects—CISA, the Freeboard Value Approach (FVA), the 0.2-Percent-Annual-Chance (500-year) Flood Approach (0.2PFA), and the elevation and flood hazard area that result from using any other method identified in an update to the FFRMS. The FFRMS identifies CISA as the preferred approach when data to support such analysis are available.[3] The 2015 CISA Appendix[4] defined "best-available, actionable science" as a primary criterion for whether a particular dataset, model, or analytical approach is appropriate for an agency to use in a CISA analysis. This report describes additional criteria relevant to the use of actionable models and the application of climate scenarios within the CISA, and helps users identify situations where more detailed study is needed (e.g., complex coastal or riverine systems) or where the action requires more robust engineering analysis.

The state of the science is described in the context of four types of flooding—coastal, riverine, pluvial, and compound. This report introduces two flood hazard projection workflows that describe the elements that are recommended to be considered when applying CISA for coastal- and riverine-related flooding, the two flooding types where present understanding is most mature. These flood hazard projection workflows also provide an overarching framework for users to understand where new data and science, including new information on climate change, feed into the process of assessing and projecting future flood hazards. The novel workflows provide additional detailed guidance for five elements of a CISA analysis: project planning and agency considerations; climate and other environmental conditions; hydrology (riverine) or stillwater (coastal) predictions; hydraulics (riverine) or wave effects (coastal); and data sharing and visualization. These

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1 *See* https://www.fema.gov/sites/default/files/documents/fema_implementing-guidelines-EO11988-13690_10082015.pdf

2 *See* "Appendix H: Climate-Informed Science Approach and Resources". 2015. Guidelines for Implementing Executive Order 112988, *Floodplain Management*, and Executive Order 13690, *Establishing Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input*. https://www.fema.gov/sites/default/files/documents/fema_IGA-appendices-a-h_10082015.pdf

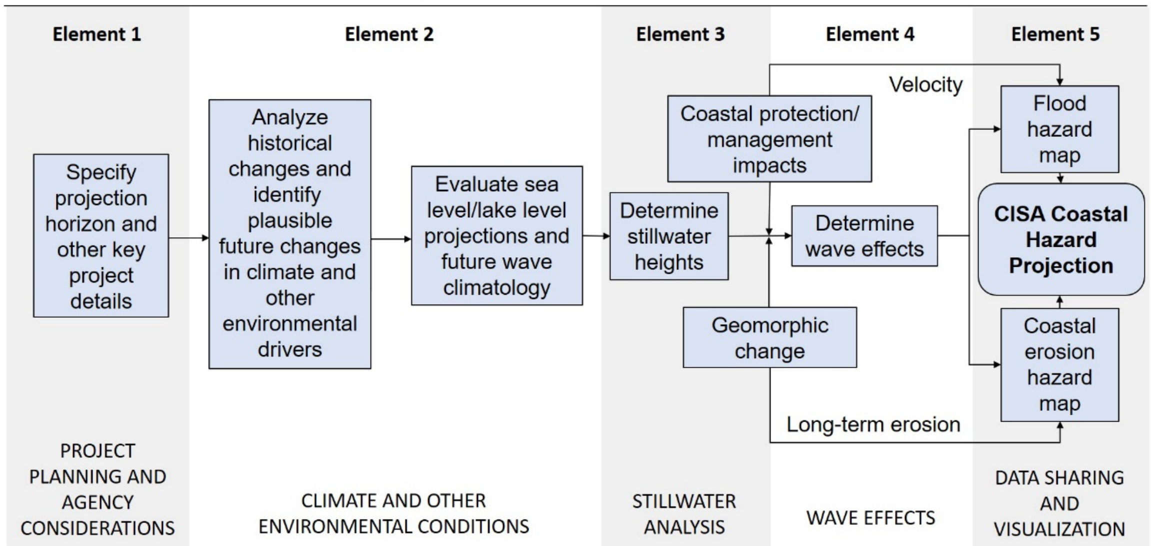
3 *See* "Appendix G: Federal Flood Risk Management Standard". 2015. Guidelines for Implementing Executive Order 112988, *Floodplain Management*, and Executive Order 13690, *Establishing Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input*. https://www.fema.gov/sites/default/files/documents/fema_IGA-appendices-a-h_10082015.pdf

4 *See* https://www.fema.gov/sites/default/files/documents/fema_IGA-appendices-a-h_10082015.pdf

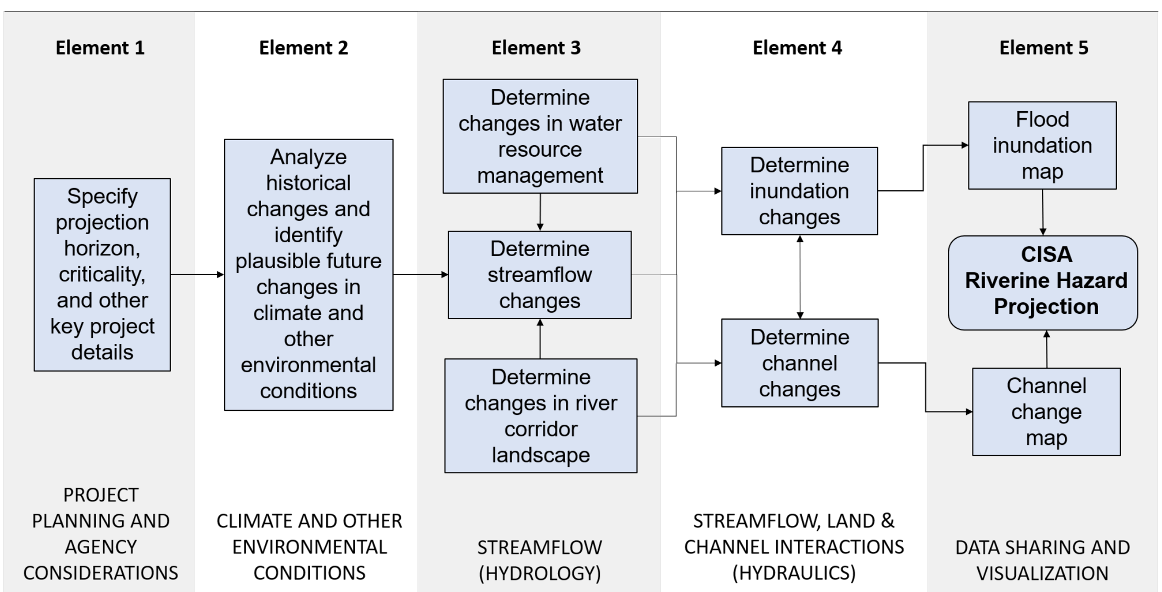
workflows can also be used to evaluate multiple scenarios of change that a given site may experience over a given planning horizon (see Section II.B). Additional workflows may be developed as analyses of pluvial and compound flooding become more mature, and for areas that are influenced by riverine and coastal flooding, it may be beneficial to consider both workflows and combine them with information and knowledge surrounding compound flooding.

With the workflows as an organizing construct, this report identifies advances in understanding and actionable science across all four flooding types. Unique considerations are captured for specific regions, such as the Great Lakes and Alaska, along with overarching issues (e.g., land use change) that either span flooding types or require integration across workflow elements.

**CISA coastal flood-hazard projection workflow**




**CISA riverine-hazard projection workflow**



For coastal flooding, key advances in understanding include:

- Updated sea level rise observations and projections;
- Hydrodynamic flood modeling; and
- Wave effects.

New progress in understanding of riverine flooding encompasses:

- Climatic changes and meteorological drivers, especially precipitation;
- Comparisons of different hydrologic modeling techniques for projecting future floods;
- Nonstationary flood frequency analysis methods for detecting observed trends in the magnitude and frequency of floods and using them to update design flood events to reflect current conditions;
- Methods for accounting for river corridor landscape change in floodplains for regulatory and planning purposes that have been implemented at State and regional levels; and
- Applicability of multidimensional hydraulic modeling.

New developments in understanding of pluvial flooding include:

- Urban flooding;
- Flooding in leveed areas or in areas with flood risk management structures; and
- Transportation assets.

Improvements in the estimation of compound flood risk are also described.

This report also provides a roadmap of needs and opportunities for improving the availability and quality of CISA analyses across the four primary flood types. The needs and opportunities for coastal flooding include:

- Ongoing and expanded monitoring of sea level rise;
- Identifying observational and research needs for the development and application of geomorphic change models in different coastal settings; and
- Nonstationary flood frequency analysis
- Understanding the role of wave effects in high-hazard areas.

The needs and opportunities for riverine flooding include improvements in:

- Analysis of hydrologic impact of different climate scenarios using both statistical methods and process-based hydrologic simulation models;
- Mixed population analyses that recognize different flood-generation mechanisms in the analysis of floods;
- Evaluations of nonstationary flood frequency analysis methods for application;
- Applications of multidimensional hydraulic modeling; and
- Methods for quantifying channel change corridor zones based on geomorphic settings.

Needs and opportunities for pluvial flooding focus on gaining a better understanding of this flood risk at a national scale and integrating these risks with other flood types such as high-tide flooding and other chronic hazards. Needs and opportunities for compound flooding include further development of statistical models, including for modeling the seasonality of floods, and more sophisticated numerical models that can more accurately represent the complex physics of the systems and factors that cause these floods.

The report includes a section on areas without FEMA base flood elevations or flood insurance rate maps. In these areas, there is a need to both better understand the challenges of implementing CISA using existing resources, as well as opportunities to work towards a future state where comprehensive flood hazard data are accessible everywhere.

The report highlights the need for, and calls for continued collaboration on, advances in flood science. One potential mechanism for this collaboration could be a community of practice (CoP) on future flooding that is embedded in an existing interagency science coordination body with the capacity to engage non-Federal scholars and contributors. The section of the report entitled "Roadmap: Needs and Opportunities to Improve Projections" could serve as a starting point for future collaboration.

# I. Introduction and Report Rationale

Flooding is the most common and costly natural hazard in the United States (Smith 2020), inflicting damage on the Nation's public health, safety, infrastructure, economic prosperity, and national security. Flooding is also an important natural phenomenon; high water flows, storm surges, and associated redistribution of sediment and nutrients during floods are critical to the health of myriad species and their habitats, and can provide an array of societal benefits (e.g., improved water quality and water supply).

Flood hazards are ever-evolving, reflecting both changes in atmospheric and oceanic drivers and as a response to natural and human modification of landforms, vegetation, and the built environment. Climate change is expected to continue to have significant impacts on future flood hazards, with effects varying temporally and spatially around the United States (Wuebbles et al. 2017; Reidmiller et al. 2018).

Recognizing the potential for losses caused by flooding to affect the environment, economic prosperity, and public health and safety, in January 2015 President Obama issued Executive Order (EO) 13690, *Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input* (Executive Office of the President 2015). EO 13690 amended and built upon EO 11988, *Floodplain Management* (Executive Office of the President 1977) and its implementing guidelines (Water Resources Council 1978), which requires agencies to take action to reduce the risk of flood loss; to minimize the impact of floods on human safety, health, and welfare; and to restore and preserve the natural and beneficial values served by floodplains. When Federal actions cannot be practicably located outside of a floodplain, EO 11988 and follow-on guidance issued by the Federal Interagency Floodplain Management Task Force (FIFM-TF 1988) required agencies to ensure that those actions were resilient to the base flood (or the 1-percent-annual-chance or 100-year flood), or the 0.2-percent-annual-chance flood (500-year) flood for critical actions.[5] EO 13690 established a Federal Flood Risk Management Standard (FFRMS) to address current and future flood risk and ensure that project funded with taxpayer dollars last as long as intended. The FFRMS requires agencies to expand management from the current base flood level to a floodplain based in one of four approaches:

1) **Climate-Informed Science Approach (CISA)** – The elevation and flood hazard area that result from using the best available, actionable hydrologic and hydraulic data and methods that integrate current and future changes in flooding, including climate change and other physical processes (e.g., land use change).
2) **Freeboard Value Approach (FVA)** – The elevation and flood hazard area that result from adding an additional 2 feet to the base flood elevation (BFE) for non-critical actions and by adding an additional 3 feet to the BFE for critical actions.
3) **0.2-Percent-Annual-Chance (500-year) Flood Approach (0.2PFA)** – The area subject to flooding by the 0.2-percent-annual-chance flood.

[5] "Critical action" means an action for which even a slight chance of flooding is too great. These actions include construction, substantial rehabilitation, or repair of facilities such as hospitals and nursing homes (which are likely to contain occupants who may not be sufficiently mobile to avoid the loss of life or injury during flood and storm events), emergency operation centers, power generating plants, and water supply and treatment facilities. For more information, see 44 Code of Federal Regulations § 9.4.

4) The elevation and flood hazard area that result from using any other method identified in an update to the FFRMS.

While EO 13690 gives Federal agencies discretion to select from among the four approaches, the FFRMS states that the CISA is preferred when data to support such analysis are available.[6] Federal agencies are presently developing policies and procedures to implement the FFRMS in the context of their authorities and programs; these policies and procedures may specify which of the FFRMS flood determination approach(es) will apply. This report is informational in nature, and does not supersede any Federal department or agency policy or procedure on FFRMS application.

## A. What Is the CISA?

In October 2015, the Water Resources Council issued updated interagency implementing guidelines for EOs 11988 and 13690, including Appendix H, which provided details on which data, models, and methods constituted the CISA[7] (herein referred to as the 2015 CISA Appendix) (Water Resources Council 2015). That document reflected the state of the science on the anticipated impacts of climate change, current up through the Third National Climate Assessment (NCA) (Federal National Climate Assessment and Development Advisory Committee 2014), and provided information on other non-climatic physical processes that can affect future flooding (e.g., land use change, landform change). Critically, the 2015 CISA Appendix defined "best-available, actionable science" as a primary criterion for whether a particular dataset, model, or analytical approach would be appropriate for an agency to use in a CISA analysis. The document stopped short of prescribing or directing agencies to use specific resources or methods.

Since October 2015, the state of science in assessing future flood hazards has evolved considerably. This CISA State of the Science report provides updated scientific concepts, data sources, methods, and considerations that complement and augment the material published in the 2015 CISA Appendix, including generalized flood risk projection workflows showing the key components of coastal and riverine future flood analyses. This report also identifies critical gaps in current understanding or capabilities to project future flood hazards, which can inform new work by the research and applied science communities and ultimately result in expanded availability and enhanced quality of CISA data to support FFRMS implementation.

As with the 2015 CISA Appendix, this report is intended to serve as non-prescriptive, scientific and engineering guidance that Federal agencies, their non-Federal partners, and other entities can use in determining future flood hazards under the FFRMS' CISA option. The technical competencies and capabilities needed to apply the CISA will likely exceed those available in most Federal agencies and to many non-Federal users; see content on "Analysts' experience and training" in subsection C below for more information. The Federal Government is working to develop additional guidance and decision-support tools to increase access and understanding of

[6] *See* "Appendix G: Federal Flood Risk Management Standard". 2015. *Guidelines for Implementing Executive Order 11988, Floodplain Management, and Executive Order 13690, Establishing Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input*. https://www.fema.gov/sites/default/files/documents/fema_IGA-appendices-a-h_10082015.pdf

[7] *See* "Appendix H: Climate-Informed Science Approach and Resources". 2015. *Guidelines for Implementing Executive Order 11988, Floodplain Management, and Executive Order 13690, Establishing Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input.* https://www.fema.gov/sites/default/files/documents/fema_IGA-appendices-a-h_10082015.pdf

best-available, actionable climate data and flood science to users applying the FFRMS to their projects.

## B. Report Scope and Structure

As with the 2015 CISA Appendix, this report uses a risk-based framing approach (i.e., how agencies may consider current and future flood risks over the lifetime of the investment or project) and assesses best-available, actionable science for different flood sources. Following this introduction, key overarching concepts of flood sources and a generic CISA workflow for all considered flood sources are introduced. Section II (Overarching Technical Considerations) addresses the adopted definitions of best-available data and actionable science. Each flood source, coastal (including the Great Lakes) (III. Assessing Future Coastal Flooding) and riverine (IV. Assessing Future Riverine Flooding), are then discussed in more detail. The report introduces consideration of pluvial flooding (V. Assessing Future Pluvial Flooding) and more in-depth considerations for concurrent or compound hazards (VI. Assessing Future Compound Flooding).

For each flooding source (including compound hazards), the initial discussion covers key scientific principles, data sources, models, and methods, updating or expanding upon information provided in the 2015 CISA Appendix. The report provides two flood risk projection workflows, one each for coastal and riverine flooding. These workflows illustrate the key components of each type of analysis and show where specific datasets (including climate data), models, and other technical materials are incorporated in a multi-step (and sometimes iterative) process to ultimately deliver actionable hazard information—that is, in a form that supports a decision or action, such as a design flood elevation, a mapped inundation extent, or other mapped hazard.

This report focuses on where and how climate data factor into future flood analyses, but does not attempt to describe all potential applications of climate data or go into detail on how such data are developed. Section II.B. (Use of Climate Scenarios within CISA) below provides some key considerations for use of climate scenarios in analyses of future flood hazards and ways to address associated uncertainty.

## C. Common CISA Concepts and Workflows

Two workflows, each tailored to the two major flooding sources (coastal and riverine), are introduced to provide agencies with the key considerations in an assessment of future flood risks. The workflows are not intended to be prescriptive; they are intended to help Federal agencies organize and understand these considerations and facilitate the identification of actionable science and methods. Although the elements within the workflows are identified discretely, there is significant interplay between and among them. During the CISA, iterations that require revisiting decisions made in early elements and investigating alternative paths are possible, even likely. While there are necessary and specific process differences between the coastal and riverine workflows, there are common elements and similar structure. The subsequent sections will describe the workflows in detail. Figure 1 provides a common framework for how each workflow is structured.

| Element 1 | Element 2 | Element 3 | Element 4 | Element 5 |
|---|---|---|---|---|
| PROJECT PLANNING AND AGENCY CONSIDERATIONS | CLIMATE AND OTHER ENVIRONMENTAL CONDITIONS | SPECIFIC TO RIVERINE OR COASTAL (HYDROLOGY) | SPECIFIC TO RIVERINE OR COASTAL (HYDRAULICS) | DATA SHARING AND VISUALIZATION |

*Figure 1: General CISA Workflow*

### *Element 1: Project Planning and Agency Considerations*

There are multiple approaches to modeling coastal and riverine flooding and geomorphic processes, including the impacts of climate change. Selection among them depends on many factors, including project requirements, agency policies, the experience and training of the analysts, and the availability of data needed to perform the site analysis.

**Project requirements:** Project requirements include constraints or limits on project location, ground elevation and constructed elevation (e.g., first habitable floor, basements, utilities), service life, structural vulnerability, service criticality, size, and likely environmental consequences that may accompany exposure to flood waters. These requirements will translate into the identification of flood vulnerabilities (including the potential consequences of project failure or inaccessibility) and the time horizon over which potential changes in flood risks must be considered, all of which is important input for Elements 2 and 3 of the workflow. For example, depending on the service life of the project, multiple planning horizons may be necessary for defining the FFRMS floodplain when assessing flood risks. Multiple scenarios might be used as part of a broader risk management approach and considered, as possible, in project planning to evaluate risks across a range of conditions and to identify trigger points and thresholds that guide alternative solutions.

When assessing the vulnerability of a project to future flooding, a risk management approach should be taken. The identification of future changes in flood levels to inform project decisions should be guided by the risk inherent in planning, designing, and implementing particular types of projects and by their location. For example, projects with high consequences from failure may require more risk-averse criteria than projects with lower consequences of failure. Therefore, scenarios should be communicated in the context of risk tolerance (even if just qualitative) to improve transparency and credibility (see Box A).

*Box A. Risk Tolerance*

Agencies evaluate action time horizon and the ability to revisit an action over time. For actions in which the consequences are low (high tolerance for risk) and the decision can be revisited over relatively short timeframes, a narrow range of less extreme scenarios may suffice for risk management. For an action in which the consequences are significant (low tolerance for risk) and which may constitute an irreversible decision that needs to operate over a relatively long timeframe, a wider range of scenarios or at least a consideration of the higher-end scenarios may be appropriate. A hybrid approach also may be considered in which a decision can be phased in over time, such that a lower set of scenarios can guide decision-making in the near- (5 to 20 years) to moderate-term (20 to 35 years), while not precluding the capability to respond to the more extreme scenarios in the longer term (Hinkel et al. 2015).

**Agency policies:** Agencies have commonly invested in analytical tools and models or use approaches developed or endorsed by other agencies that detect, attribute, and model climate-change impacts on their investments. In addition, some agencies are regulatory in nature and thus require rulemaking, and others will implement FFRMS as a matter of policy in environmental compliance procedures. Agency policy may influence or require a CISA workflow, as supported by the 2015 IG (Water Resources Council 2015) and informed by the new understanding and approaches contained in this State of the Science report. In all cases, the 2015 CISA Appendix and this State of the Science report were developed to promote consistency while allowing flexibility in implementation based on individual agency criteria, including capturing what would be most scientifically credible when there are options among approaches, datasets, or models. For example, it states that future coastal flood hazard analysis should combine changing climate conditions (e.g., sea level/lake level change) with surge, tide, and wave data using methods appropriate to policies, practices, criticality, and consequences. The 2015 CISA Appendix is also clear that changes in land use (particularly the impacts of urbanization and increases in imperviousness), in water management practices (such as the altered operation of dams), and in the presence of burned areas should be considered in projections of future riverine flood hazards.

**Analysts' experience and training:** The experience, training, and preferences of project analysts may also affect CISA implementation. Full implementation of the coastal workflow requires extensive hydrodynamic modeling experience; familiarity with flood frequency statistics; and coastal geology, engineering, and geographic information system (GIS) expertise. Implementation of the riverine workflow requires expertise in hydrologic, hydraulic, statistical, and geomorphic modeling. In both cases, workflow implementation can be scaled to meet resource level and project requirements. Some agencies have established centralized units that are responsible for climate studies and are well-positioned to conduct and/or evaluate CISA analyses. Other agencies could consider collaborations with agencies with technical skills and experience in CISA techniques.

**Data availability:** Data availability greatly influences the feasibility of various analytical approaches and the scope of model simulation. Data availability challenges can include *in situ* measurements/observations (gauges) that only capture processes at a point/small area and are often not dense enough to capture regional differences. Climate modeling is often done at a coarse spatial resolution, requiring downscaling for regional or local analysis. Remote-sensing techniques have limitations (e.g., light detection and ranging [LiDAR] sensors will not see through turbid water, and interferometric synthetic aperture radar [InSAR] cannot see through tree canopy). Many areas are remote and inaccessible, making it cost-prohibitive to collect data. Some locations lack tidal datums or convenient access to geodetic control for consistently tying *in situ* or remote observations into the National Spatial Reference System (NSRS). Data priorities often focus on more accessible/populated areas, making remote, rural, and/or uninhabited areas data-poor. In all cases, monitoring data will improve calibration and validation of remote sensing models.

Examples of data issues include the availability of historical coastal water level data due to spatial resolution (only at tide gauges or buoys) and length of records (e.g., 30 years of data needed for a trend analysis—38 preferred for more statistical robustness), wave climatology records, accurate digital elevation models, land use information for frictional coefficients and change analyses, and surveyed shore normal cross sections. Examples of data issues for riverine flooding include future rainfall intensity-duration-frequencies (IDFs), length and relevance of nearby precipitation or streamflow data, land use information, and geomorphic histories.

### *Element 2: Climate and Other Environmental Conditions*

This element aims to determine whether there are substantial changes (e.g., nonstationarity) observed in the historical record and if projected physical change processes will change flooding over time. In most instances, substantial changes in climate variables (heat, precipitation, sea level rise [SLR]) have occurred or are projected. These changes likely warrant analysis using CISA methods that characterize changes in the flood elevations and extent over time (with attribution to identified drivers, if possible). Identifying and correlating potential drivers of change in flooding increases confidence that the change is not due to natural variability (Hodgkins et al. 2019; Woodruff et al. 2013). Drivers of change that have been attributed to observed and projected changes in flooding include both changes in climate and land use.

### *Elements 3 and 4: Hydrology, Hydraulics, and Hydrodynamics*

These elements are specific to the workflow of interest and are addressed in detail within the coastal and riverine sections.

### *Element 5: Data Sharing and Visualization of Flood Hazard Data*

This final element of the workflow addresses the visualization of predicted flood hazards (depths and inundated areas) and geomorphic hazards identified in Element 4. Common methods for communicating inundation hazards include tables with flood elevations by location based on transects or cross sections, and maps with discrete flood zones or graduated risk zones based on probability. Required regulatory and floodplain management decisions necessitate use of those existing zones of special flood risk. However, the intended workflow outcomes seek to identify future flood risk zones to inform future Federal investments. FEMA Flood Insurance Rate Maps (FIRMs), one of the most visible and well-known mapping products, though not available nationally, provide specific flood zones and base flood elevations (BFEs).[8] Details of inundation and geomorphic hazards mapping as they relate to both the coastal and riverine workflows are addressed in more detail in subsequent sections.

### *Roadmaps*

The Appendix of this report summarizes conceptual roadmaps identifying needs (gaps) requiring improved science and methods for the four flood types and illustrating the relationships among many of these needs. Indeed, many of the science gaps have cascading implications, while many of the suggested improvement actions are mutually reinforcing. The roadmap also reveals the multi-agency character of these needs in which tools and data from multiple agencies need to come together to permit actionable CISA applications. The roadmap indicates an approximate timeline for investments including short-term (less than 1 year), medium-term (1–5 years), and long-term (more than 5 years). The temporal banding is based on assessments by agency representatives, informed by existing and planned agency capabilities, and subgroup consensus.

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[8] A BFE is "the elevation of surface water resulting from a flood that has a 1% chance of equaling or exceeding that level in any given year." FEMA, 2020. "Base Flood Elevation (BFE)." https://www.fema.gov/node/404233

# II. Overarching Technical Considerations

## A. What Is "Best-Available, Actionable Science" for CISA?

The 2015 CISA Appendix established the terms "best available" and "actionable" to help Federal agencies identify what data or science should be applied in the CISA. As stated in the Appendix:

**Best-Available Data and Science** are:

- **Transparent** – clearly outlines assumptions, applications, and limitations.
- **Technically credible** – transparent subject matter or more formal external peer review, as appropriate, of processes and source data.
- **Usable** – relevance and accessibility of the information to its intended users. For the CISA approach, usability can be achieved by placing climate-related scenarios into appropriate spatial, temporal, and risk-based contexts.
- **Legitimate** – perceived by stakeholders to conform to recognized principles, rules, or standards. Legitimacy might be achieved through existing government planning processes with the opportunity for public comment and engagement.
- **Flexible** – scientific, engineering, and planning practices to address climate change-related information are evolving. To respond, agencies need to adapt and continuously update their approaches consistent with agency guidelines and principles.

**Actionable Science** consists of theories, data, analyses, models, projections, scenarios, and tools that are:

- **Relevant** to the decision under consideration.
- **Reliable** in terms of its scientific or engineering basis and appropriate level of peer review.
- **Understandable** to those making the decision.
- **Supportive of decisions** across wide spatial, temporal, and organizational ranges, including those of time-sensitive operational and capital investment decision making.
- **Co-produced** by scientists, analysts, and decision makers, and meet the needs of and are readily accessible by stakeholders.

Although models were included as a dimension of actionable science above, additional criteria may be helpful to those weighing whether a particular model or modeling approach would be appropriate or advantageous in a CISA analysis.

- **Actionable models are well-established in practice**, meaning reviewed, tested, well-documented, and accepted by each agency's criteria and/or approved by FEMA (2022a). This criterion ensures that it is relatively less likely that revisions to address errors or unexpected behaviors are required, and that results should have a longer useful life and be less subject to retraction.
- **To the greatest extent practicable and as appropriate, actionable models should rely on representation of physical processes in ways that are not oversimplified and based in scientific understanding of those processes.** This process fidelity helps ensure that models

produce the right answers for the right reasons, which is particularly important when simulating events outside the domain of the training data, as is often the case for events affected by climate change.

- **Actionable models, used appropriately, should not extrapolate results into areas beyond those where the underlying mathematical relationship (or forcing independent variables) can reasonably be expected to apply.** Empirical functions or statistical models used for simulation should be constrained to combinations of conditions where their outputs can plausibly be considered reliable. Constraints for modeling approaches without strong process fidelity will typically not extend beyond the limits of the training data used to fit the statistical model or parameterize the empirical function.
- **Actionable models should explicitly display information about the uncertainty of results, as well as the expected value of those results.** Information about uncertainty may be in the form of confidence intervals, prediction intervals, probabilities of assurance, credible intervals, or other established approaches.
- **Actionable models should be well-calibrated to observed data, and validated using independent datasets.** Bootstrapping or other techniques should be used to ensure that model performance does not rely on the same data used to train the model, to avoid overfitting. Validation statistics will typically use well-known and understood measures of error or efficiency, or statistical hypothesis tests of goodness-of-fit between observed and modeled data.
- **Actionable models should not produce outputs that indicate a failure to represent physical processes appropriately, even if the overall outputs show good performance compared to observed data.** For example, simulated floods should occur in their appropriate seasons of the year, regardless of whether flood magnitudes show good agreement with observed measurements.
- **Actionable models should provide outputs that are understandable to the intended audience.**
- **Actionable models should be evaluated through an expert elicitation or peer-review process that can assess and characterize the models' actionability.**

## B. Use of Climate Scenarios within CISA

No one can precisely predict the future flood conditions that may result from global climate change. Indeed, nations around the world are actively debating, and in some cases adopting, policies and practices designed to reduce the principal driver of anthropogenic climate change, greenhouse gas (GHG) emissions. For this reason, and because of uncertainties in the response of the climate system to a given GHG emissions pathway, future flooding conditions will remain highly uncertain. Thus, for the foreseeable future, the best approach for assessing future hazards associated with all types of flooding examined in this report (riverine, coastal, pluvial, compound) usually is to rely on analysis of multiple plausible and decision-relevant climate scenarios. Below are a few considerations for climate scenario selection, with references that can provide more details.

The rapid expansion of computational power has enabled the development of Global Climate Models (GCMs), which simulate climate impacts of different atmospheric GHG concentration trajectories. Many recent climate-impact studies, including NCA reports (e.g., Reidmiller et al. 2018), have used scenarios of climate change resulting from different GHG emissions pathways, that are derived from the GCMs evaluated in the Coupled Model Intercomparison Projects (CMIPs) sponsored by the Intergovernmental Panel on Climate Change (IPCC). Still, the mesh or grid size remains an issue for use of these GCM outputs to evaluate flood risk. Using a 60 x 60-km grid does not yield sufficient resolution to capture most project-level watershed or drainage areas. Various "downscaling"[9] and "bias-correcting"[10] algorithms have been developed to extend estimates to smaller scales and basins and more localized climates. The Bureau of Reclamation provides access to compilations of multiple downscaled and bias-corrected GCM datasets (World Climate Research Programme 2007).

In many cases, both raw and post-processed (i.e., downscaled and bias-corrected) simulations from given GCMs may not produce reasonable climate statistics during a historical period or may not simulate the primary atmospheric circulation mechanisms well; for example, they may not have the ability to characterize the frequency and intensity of storms which would be of particular importance to the impact of flooding (Thibeault and Seth 2014; Srivastava et al. 2020). In such instances, a model selection process may be undertaken to reduce the ensemble of GCM-derived scenarios to ones that best reproduce historical statistics and atmospheric circulation mechanisms. However, there is no consensus standard for model culling or selection. Both are best left to expert climate modelers who understand the behavior of specific models and the risks and benefits of including or excluding specific candidate models.

On the other hand, GCM-derived climate scenarios do not represent an exhaustive set of potential climate futures. In some instances, the omission of other more extreme—yet plausible—changes in climate can obscure important climate tipping points, leading to undesirable planning decisions. To curtail this risk, some studies have recommended "bottom-up" or "stress-testing" approaches (Brown et al. 2012) that examine the response of systems, including floodplains (Spence and Brown 2018), to a large number (dozens to thousands) of plausible climate futures. These large sets of plausible climate futures may be informed by GCM-derived scenarios but, importantly, are not limited to them.

Selecting a set of plausible GCM-derived climate scenarios for a region—whether derived solely from GCMs or from "bottom-up" stress-testing approaches—is just one step of the process for identifying the "best-available, actionable" climate information for a CISA application. Critically, identifying the best-available, actionable climate information also involves the consideration of climate change uncertainty.

Floodplain managers and stakeholders often evaluate tradeoffs between the over-design and under-design consequences of their potential decisions under a range of plausible climate futures (e.g., Rosner et al. 2014; Spence and Brown 2018; Hecht and Kirshen 2019). Complicating matters

[9] Downscaling refers to methods and techniques used to process and refine GCM outputs to finer levels of spatial resolution. *See* NOAA Geophysical Fluid Dynamic Laboratory. N.d. "Climate Model Downscaling". https://www.gfdl.noaa.gov/climate-model-downscaling/

[10] Bias correction refers to methods and techniques used to account for the ways GCM outputs deviate from observed data due to their limited spatial resolution or simplified physical or climatic processes with the aim of making these outputs more realistic. *See* Copernicus Climate Change Portal. N.d. "What is Bias Correction?" https://climate.copernicus.eu/sites/default/files/2021-01/infosheet7.pdf

further, experts are commonly hesitant to assign probabilities to individual climate scenarios (Dessai and Hulme 2004). However, in recognition of this “deep uncertainty” (Hallegatte et al. 2012), numerous ”robustness” metrics that can compare the range of potential over- and under-design consequences of projects under a set of different climate scenarios, such as minimax regret, robust decision making, and adaptive pathways approaches, have been advanced (e.g., Haasnoot et al. 2013; Herman et al. 2015; McPhail et al. 2018).

The selection of such metrics for future flood hazard evaluation often reflects the degree of risk aversion associated with the criticality of a project.[11] Importantly, the use of scenario simulations, robustness metrics, and low-regret design strategies is becoming an increasingly accepted and commonly employed design evaluation practice even in engineering fields unconcerned with climate change. Used properly, they may reveal project susceptibility to extreme events and then provide an opportunity for their associated consequences to be mitigated.

Adding consideration of the relevance of climate change scenarios to flooding is an important and challenging advancement, but it is well within the realm of expert analysis. Additional guidance regarding the incorporation of agency considerations and project characteristics into climate scenario selection is presented in later sections focused on specific flood hazards.

## C. Considerations for Non-Climatic Drivers of Changing Flood Hazards

Changes in the use, cover, and management of land have all been associated with changes in flooding (e.g., Leopold 1968; Wagenbrenner et al. 2021). These changes can affect the magnitude and timing of runoff generation, the routing of flow to channels, overland wave generation and attenuation, and the depth of inundation in riverine and coastal floodplains.

Land use refers to the change in the activity for which land is being used (for example, agricultural versus urban). Land cover refers to biophysical properties of the land surface. For example, a recently burned forest will have different soil properties and much less canopy cover than a mature, old-growth forest. Land management refers to practices that may affect the land cover (e.g., cover crop on a field) or subsurface drainage of the land (e.g., tile drains for agricultural land or stormwater infrastructure in urban areas).

Hereafter in this report, the term “land use” is used to encompass this full suite of hydrologically relevant landscape properties. In contrast, large-scale water resources infrastructure, such as dams, diversions, and levees, are considered in a separate water resources management category. Hydrologically relevant land use metrics that could be relevant to specific elements of the CISA coastal and riverine workflows, such as impervious cover or burn severity metrics, are discussed. Most importantly, CISA provides a framework for considering the potential effects of land use change on current and future flooding.

## D. Interpretation of Flood Risk Under Nonstationary Conditions

In its definition of the CISA, EO 13690 refers to “methods that integrate current and future changes in flooding based on climate science.” While the word “integrate” is normally understood to mean “bring together” or “combine,” it also has a mathematical definition. As a result, the phrasing of

[11] See McPhail et al. (2018) for a comparison of the implications of these robustness metric choices for a stylized flood management case.

the order is somewhat ambiguous, and at least two possible interpretations of CISA methods are possible. The main body of this document interprets the order to mean that when conditions are changing over time, the CISA will yield the elevation and flood hazard area corresponding to the worst-case conditions over the period of analysis. This ensures that as conditions change over the period of analysis, projected risk will never exceed the hazard developed under the CISA. In certain cases, however, it may be preferable to depict a flood hazard area that represents the expected value of flood hazard over the period of analysis. The distinction between these two interpretations, and methods for assessing risk under the second definition, are explored in detail in Appendix B.

# III. Assessing Future Coastal Flooding

This section describes the elements of future coastal flood analyses using a coastal workflow (Figure 2) as a conceptual framework for describing the hazard-projection process, to report on new applicable science, and to identify a roadmap for bridging science and methodology gaps.

## A. Coastal Workflow

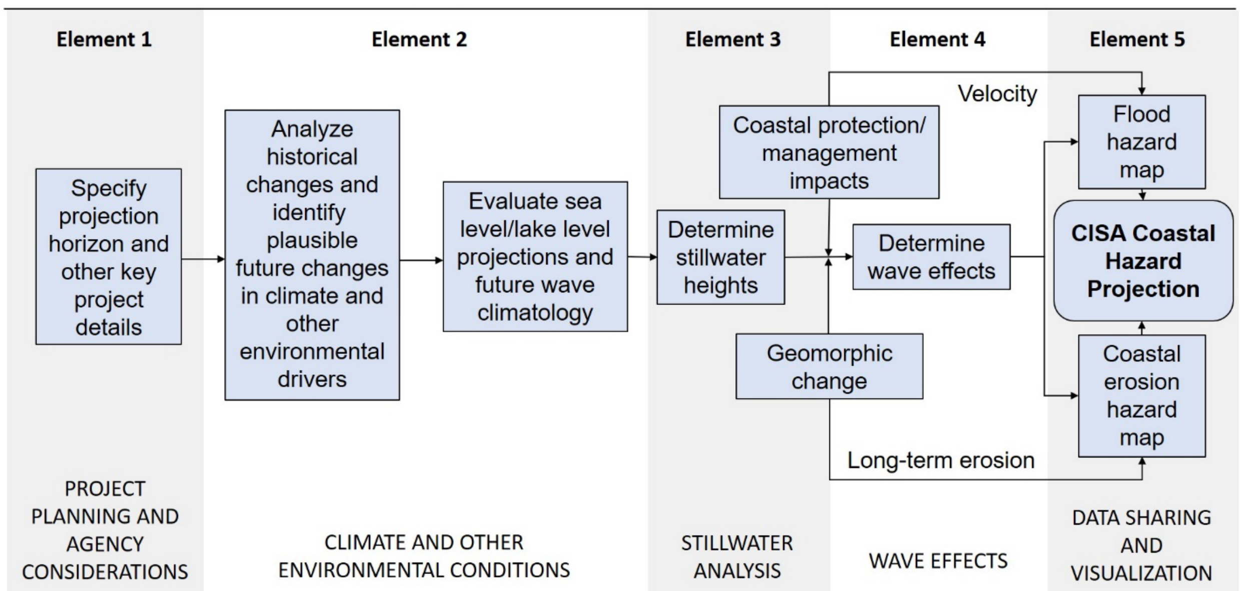


*Figure 2: Workflow for CISA coastal flood analysis*

The initial coastal workflow element requires the analyst to consider project requirements such as location, criticality, service life, consequences, design or project evaluation criteria, and site and structure elevations, all of which inform decisions made in subsequent elements of the analysis. The second element on climate and other environmental conditions includes likely changes in mean sea or lake level, vertical land motion (VLM) rates, changes in wave climate, and sea ice reduction in cold regions. As part of this element, analysts will need to establish a strategy for analyzing historical changes and determining potential future changes in climate and other environmental drivers. This may include evaluating flood frequencies (e.g., 1-percent-annual-chance-flood) and determining how that frequency will change in the future (e.g., 1-percent becomes the 10-percent-annual-chance-flood). Dynamic, process-based models typically require input on potential future changes to sea or lake levels as well as any potential changes to the wave climate and land use.

For Elements 3 and 4 of the coastal analysis, analysts should factor in the impacts of both natural and human-made geomorphic changes. A variety of 1D, 2D and, 3D coastal process models are available for efficiently modeling hydrodynamic (stillwater) and wave setup effects (Figure 3). Dynamic stillwater level as shown in Figure 3 is consistent with the way in which FEMA includes wave setup in stillwater modeling, but a user should determine whether wave setup is included in the data source being used. Project details inform whether changes in coastline morphology, vertical land level, coastal management plans or structures, or site-specific wave conditions that may affect overland propagation, runup, overtopping, or episodic erosion should be considered and integrated. Finally, the last element, if it is needed for the project, is to communicate (e.g., via inundation/hazard maps or flood elevations) the flood extent, depth, wave impacted velocity zones, and erosion hazard areas.

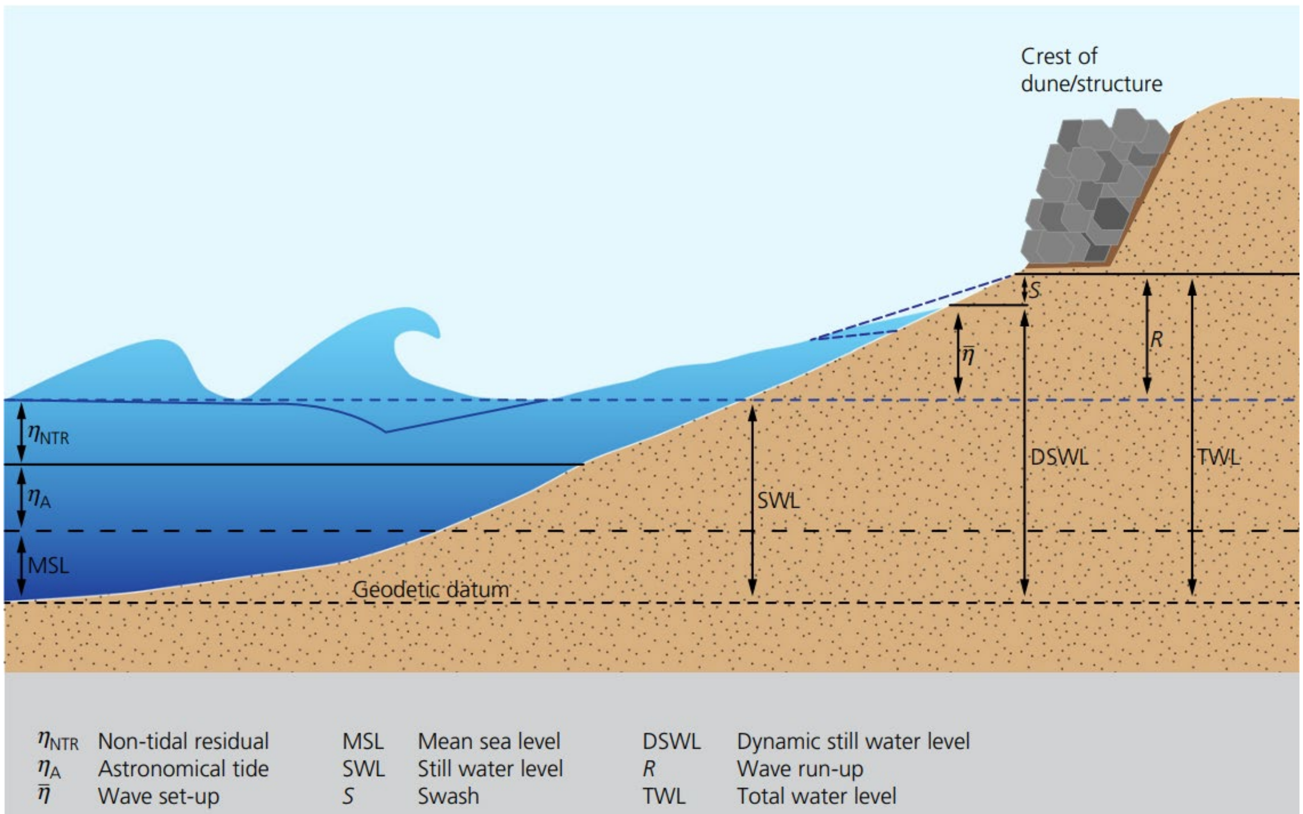


*Figure 3: A profile depiction of the component approach to coastal flooding (Moritz et al. 2015)*

### ***Element 1: Project Planning and Agency Considerations***

Under EO 13690, agency actions and project designs need to consider adaption to future flood risks that may require modeling. There are multiple approaches to modeling coastal and nearshore processes to determine flood and erosion hazards. In addition to project requirements and agency policies, modeling in either coastal or riverine situations will require consideration of the availability and relevance of data.

### *Element 2: Climate and Other Environmental Conditions*

This element aims to determine whether there are substantial changes (e.g., nonstationarity) observed in the historical record and if projected physical changes in coastal water levels and processes will increase coastal flooding over time. In most instances, substantial changes in climate variables (heat, precipitation, SLR) have occurred and/or are projected to occur. These changes likely warrant analysis using CISA methods that characterize changes in the flood elevations and extent over time (with attribution to identified drivers, if possible). Identifying potential drivers of change in flooding can avoid falsely diagnosing apparent changes in flooding due to natural variability as trends (Woodruff et al. 2013). Drivers of change that have been attributed to observed and projected changes in flooding include both changes in climate and land use/management. Changes in coastal flooding due to coastal management and protection—such as sea walls, revetments, groins, wetland or coral reef construction and restoration, and beach nourishment—are good examples and considered more in subsequent elements.

### *Element 2a: Historical Changes*

Changes in many indicators, especially metrics of change in sea and lake levels, have been associated with observed historical changes in coastal flooding. At any given moment, water levels observed along U.S. coasts and lakes vary in response to a variety of astronomical, meteorological, climatological, geophysical, and oceanographic forcing mechanisms (Nicholls et al. 2007). The analyst must try to evaluate historical changes to these mechanisms to determine how they have changed and if what was recorded in the past will persist into the future. This process, evaluating stationarity, involves statistical methods to determine if changes are linear or non-linear and what is the cause (natural variability or long-term multi-factor changes associated with climate change). The following is a list of variables that the analyst should evaluate for historical changes:

- **Global and relative sea level/lake level trends or long-term averages** – Long-tide and water level gauge records provide information on local sea level/lake level change variations. These data can be obtained from NOAA (NOAA n.d.d).

- **Extreme water levels** – Similarly, using long-term average water levels, extreme water level statistics can be developed and used for model validation (NOAA n.d.a). New gridded extreme water level data based on regional frequency analysis is now available from Sweet et al. 2022. The USACE (2022) Coastal Hazards System also provides extremes based on synthetic models vs. historical data.

- **Significant wave heights** – Wave buoy data are archived at the NOAA (2021) Data Buoy Center, which include both NOAA buoys and many partner entities.

- **Long-term erosion rates** – USGS (2017) has a national shoreline erosion product that can be used to assess long-term erosion rates on a consistent basis nationally. Individual State coastal management programs also monitor local erosion rates. Where available, these data can be used for finer spatial and temporal resolution.

- **Changes in elevation control** – The National Spatial Reference System (NSRS) enables access to heights on vertical control (benchmarks and Continuously Operating Reference Stations) across the country. Leveraging NSRS datums (e.g., NAVD 88, IGLD 85) allows for the consistent alignment of data nationwide. This accurate linkage of coastal water level data and models to the land surface and to existing and proposed infrastructure is critical at climate timescales, and particularly in areas undergoing vertical land level change (see Box B).[12] Accounting for changes to vertical datums over time (e.g., local tidal datums based on past National Tidal Datum Epochs) facilitates the evaluation of historical changes.

- **Sea and lake ice extent** – Sea and lake ice protects the coastline of many cold regions of the United States, and changes in ice extent, concentration, and character (e.g., slush concentrations) can alter wave energy conditions at the coast, influencing flood hazard extents and potentially causing higher erosion rates or changes in ice shove potential. The Sea Ice Index (National Snow and Ice Data Center 2022) provides historical trends of sea ice.
- **Land use changes** – Historical changes in land use, as well as changes to the coastline from human activities, may need to be evaluated to determine if they are potential causes of changes in any of the variables described above. For example, periodic dredging and beach renourishment may impact coastal erosion response and impact tidal dynamics and wave impacts. Land cover datasets such as the National Land Cover Dataset from USGS or the Coastal Change Analysis Program can assist with detecting change over time. Higher resolution land cover data (1-m) are becoming more available, which have enough detail for quantifying small-scale changes.

[12] Forthcoming updates to tidal (NOAA n.d.b) and orthometric datums (NOAA n.d.c) will include enhanced time-dependency that can help characterize non-uniform vertical land motion at the watershed scale for more accurate flood hazard assessments.

### *Box B. Vertical Land Motion (VLM) Considerations*

Areas subject to ground subsidence or uplift require the use of best available positional data throughout the recommended CISA workflows. Physical changes in the elevation of the land surface may include topographic variations that affect hydraulic flow patterns as well as movement that can impact the relative heights of obstruction features, project site elevations, and local vertical datums. For areas in motion, the use of epoch-specific datums and the consideration of supplemental VLM information is therefore critical to flood risk determination. These considerations are especially important when the vertical motion is non-uniform at the watershed scale or non-linear over time (e.g., due to glacial isostatic adjustment, tectonics, sediment compaction, groundwater and fossil fuel withdrawals, volcanic activity, permafrost loss, and other non-climatic factors).

In coastal areas, long-term sea level trends observed in tide station records include estimates of VLM (Sweet et al. 2022). If VLM rates in the proximity of a project site are suspected to vary from regional trends, sea level trend projections can be localized by replacing the estimated regional VLM component with a user-defined value based on hydrology and hydraulics (H&H)-based rates at Continuously Operating Reference Stations or via InSAR. Such substitutions require a critical assessment of the drivers behind observed motion to evaluate assumptions of rate projections that may vary with land use changes or as a result of fixed factors like total ice mass.

In tectonically active areas, projects with low risk tolerance can also benefit from an additional elevation to compensate for uncertainty in potential VLM based on any records of historical VLM. After large seismic events, flood hazard assessments may need to be updated based on changes to the relative vertical positions of flood sources, project sites, and other topographic differences.

#### ***Element 2b: Future Changes in Climate or Other Environmental Drivers and Evaluation of Sea and Lake Level Projections and Future Wave Climatology***

As described in Section II. B. Use of Climate Scenarios within CISA, the primary driver of climate change is the unprecedented levels of GHGs in the atmosphere and the resulting response of both atmospheric and oceanic heating. Both of these processes directly impact coastal processes and thus coastal flooding. Increases in global temperature will continue to warm the oceans, which will cause them to expand their volume. At the same time, ice in the form of land-based glaciers and continental ice sheets (Antarctica and Greenland) will continue to melt and redistribute their mass (ice sheet fingerprinting), further raising sea levels. For the Great Lakes, changes in precipitation and evaporation rates will continue to change lake levels. After an analysis of historical change as part of Element 2a, the analysis should investigate future climate change scenarios and their impact on coastal flooding. Many of the same variables need to be evaluated for projected change and provided as input into coastal hazard projection modeling. Below is a list of projection information that will be needed as input into change modeling; Section III.B below will discuss the advances in the understanding and actionable science in each:

- **SLR extrapolations and scenarios** – As part of the NCA process, new actionable and usable sea level science is updated and scenarios provided via the Federal Interagency Sea Level

Rise and Coastal Flood Hazard Scenarios and Tools Task Force (Task Force). There have been three iterations of SLR science updates as part of NCA3 (Parris et al. 2012), NCA4 (Reidmiller et al. 2018), and NCA5 (Sweet et al. 2022). Guidance in the 2015 CISA Appendix was based on the NCA3 scenarios. The latest projections have also been enhanced with historical data and extrapolations out to 2050.

- **Great Lakes water level projections** – Better historical information is now available and new science is currently being developed to improve future lake level projections. Known variables, such as high water levels that contribute to coastal flooding, can be incorporated as scenarios into future conditions flood studies.
- **Future VLM** – VLM can be an important contributing factor to local sea level changes and associated flood risk. This information is primarily incorporated into coastal flood assessments at present as a component of relative sea level changes recorded at long-term tide stations, and it is often assumed to be a constant when projecting sea level rates. However, there is known variability both spatially and temporally that is not fully captured by existing tide gauges, is non-linear (e.g., seismic and post-seismic adjustments), or is highly non-uniform at the watershed scale (e.g., subsidence associated with groundwater extraction). Actionable guidance for areas with known VLM complexity are captured within the Alaska guidance below, and new research is being completed to evaluate satellite technology (InSAR) to develop gridded regional-scale VLM rates that could be used to improve coastal, riverine, or pluvial flood risk projections in the future (see Box B above).
- **Sea and lake ice extent projections** – Future sea ice extent projection is an ongoing area of research. There is limited actionable science at this time to use for assessing the potential coastal flood risk impacts of changing sea ice duration, extent, and other characteristics.
- **Future wave climatology** – The new generation of CMIP6 climate models is now available as part of IPCC's AR6. There is ongoing research to use these data to project future wave energy that could then be used for modeling (see sections B. Use of Climate Scenarios within CISA and C. Considerations for Non-Climate Drivers of Changing Flood Hazards).
- **Point versus gridded data**– When the 2015 CISA Appendix was issued, sea-level projections and other water level frequency datasets were only available at individual tide gauges, limiting geographic coverage. SLR scenario updates by federal interagency groups in 2017 (e.g., USGS n.d.) and 2022 (Sweet et al. 2022) provided data in a one-degree grid as well as at tide gauges, enabling actionable use of the data for locations between gauges.

### *Element 3: Stillwater Analysis*

"Stillwater" is the term used in FEMA guidance as coastal stillwater levels and stillwater elevation. A stillwater level is the coastal water surface resulting from mean sea level, astronomical tides, and non-tidal residuals, such as storm surge. The stillwater elevation is the statistical elevation of the stillwater level relative to a specific datum. These values can be derived from historical or projected data, like the gridded Regional Frequency Analysis described earlier (Sweet et al. 2022) or from 2D or 3D coastal hydrodynamic and wave models, depending on the project requirements. This coastal flood scenario could be based on a specific design event, or could be based on a return period or frequency of interest.

To derive the stillwater response from a model, the first step is to define the base topography. Collaboration between Federal, State, Tribal, territorial, and local governments via programs like 3DEP (USGS 2016a) can be done to compile and develop the best available topographic and bathymetric Digital Elevation Models (DEMs). Because the coastal environment is constantly changing on a yearly, if not a daily, basis, up-to-date bathymetric and topographic data are very important. Future conditions studies may also require changing the DEM to a future projected state (e.g., include or remove coastal inlets, channels, dunes, and offshore sand features). The DEM serves as the basis for the 2D hydrodynamic modeling grids. It is also important to collect up-to-date and projected land use data if considering updated coastal modeling, as this has influence on things like the seabed and land surface roughness.

The next step is to use a coastal model to derive stillwater data. A model framework will need to be decided on and model geometry built. The model should be able to simulate the propagation of storm surge and tides and should also be able to incorporate wind stress, atmospheric pressure differentials, and the effects of wave radiation stresses. Model geometry should be sufficient to define the storm surge propagation pathways of interest to the site. FEMA (2021b) has a list of approved coastal models for use in flood studies conducted for the National Flood Insurance Program (NFIP), but these are not the only options.

A model is only useful if it is properly validated. This is typically done by looking at historical storm events. This requires the development of historical wind fields, in addition to gathering appropriate water level and wave measurements to compare.

Finally, the properly validated model can be used to derive the stillwater response of interest. In order to account for future SLR scenarios, the model setup should be changed to reflect these conditions (via the DEM, land use, initial and boundary conditions). At this phase, the analyst should examine whether the project is considering future "events" or a future response frequency, as these will require different levels of model setup and implementation. To derive future response frequencies in a modeling framework, large numbers of ensemble realizations may be required.

For a fully modeled approach to future conditions, the change scenarios should be directly integrated into the modeling system. This approach has significant technical and computational burdens that may not always be achievable in every project. Useful references and processes on the development of coastal stillwater data can be found in FEMA (2022b) mapping guidance as well as the USACE (2022) Coastal Hazards System.

### *Element 3a: Geomorphic Change (Long-Term Erosion)*

Long-term coastal erosion (LTCE) that occurs over a period of decades fundamentally alters coastal landscapes over time and can lead to substantial shifts in flood hazards. Although influenced by SLR (among many physical processes) and a major contributor to coastal flood hazards in some places, LTCE is typically depicted and managed as a separate hazard (USGS 2017). LTCE is typically represented by a shoreline location (e.g., high-water line, Mean High Water, or other proxy) and can be projected into the future based on historical erosion trends and/or modeling. Methods for determining long-term erosion rates and future shoreline locations are known as historical shoreline mapping and erosion rate analysis. Common methods such as linear trend forecasting or data assimilation techniques generally assume stationarity; that is, the predicted rate of shoreline change does not consider potential acceleration or deceleration caused by physical processes, such as changes in the rate of relative SLR (USGS and NOAA n.d.). The scientific understanding of historical shoreline mapping is very mature, and results are robust and support current development of more advanced statistical (Montaño et al. 2020) and numerical modeling methods. States and commonwealths commonly establish coastal setback lines or erosion hazard areas based on 30-year, 60-year, or other multiples of historical LTCE (e.g., Crowell et al. 1999; USACE et al. n.d.).

With regard to coastal flood mapping, two categories of erosion can be defined: storm- or event-driven erosion; and long-term erosion. Storm- or event-driven erosion is the erosion that occurs during a storm event (USGS and NOAA n.d.). Such events may have temporary or permanent, cumulative impacts on coastal flooding, depending on natural or anthropogenic processes such as beach and dune recovery, beach nourishment, or other coastal engineering. Approaches are being developed that resolve the cumulative short-term impacts of storms on LTCE using statistical methods (Vitousek et al. 2017) and numerical models (Mickey et al. 2020).

### Element 3b: Coastal Protection/Management Impacts

Human response to rising water levels likely will also have a significant impact on future coastal flood hazards. Local shoreline decisions or policies to maintain the current shoreline location through beach nourishment and/or shoreline hardening, for example, versus a managed retreat from the most highly erodible areas, will have major impacts on the extent of the future conditions floodplain (Wang et al. 2017a). Current engineered structures, such as buildings, seawalls, revetments, and, in some cases, practices such as beach renourishment, are considered within FEMA studies through the 1D-transect-based analyses for storm-driven erosion, runup and overtopping. However, these 1D-transect-based analyses may only consider/apply the 1-percent-annual-change storm condition for a single event using response-based methods. The analyses do not consider the temporal and cumulative effects upon such structures from these erosion, runup, and overtopping constituents. The long-term condition of coastal areas very much depends on the human response, and this is difficult to model. A scenario approach may be most appropriate to look at future build-out of coastal areas and combinations of gray and green infrastructure and hard and soft stabilization methods for shore protection. This information can be incorporated into future conditions models in addition to the physical process variables mentioned in the above sections.

### Element 4: Determine Wave Effects

In many coastal flood studies, wave effects are handled in two parts. Wave setup is usually included in the stillwater analysis. If the stillwater analysis is based on historical or projected data, the wave setup is inherently incorporated in the data. If the stillwater analysis is derived from a model system, the setup would be derived from coupled nearshore 2D wave models. These models can also provide output and insight into wave conditions such as height or period.

However, wave conditions in coastal areas often include a number of other components that may be important to an individual project. For example, FEMA coastal flood studies and BFEs may include components due to wave, runup, overtopping, episodic erosion, overland wave propagation for the 1-percent-annual-chance exceedance, and in some cases, other limited frequency conditions, when it would be appropriate to do so. These are separate analyses, more typically conducted with transect-based 1D models or empirical formulations. Natural features, such as dunes and bluffs, and engineered features, such as seawalls, revetments, beach renourishment, and well-established human-made dunes, can be incorporated directly through these types of analyses. FEMA (2021a) mapping guidance can provide details on these analyses, as can the USACE (n.d.a)

Coastal Engineering Manual. As with the stillwater analysis, projections of future scenarios may require direct integration with these transect-based assessments and will be dependent on future scenarios due to the change in stillwater level, the change in wave climate, and any potential changes due to land use or future coastal protection or management projects.

### *Element 5: Data Sharing and Visualization*

This final element of the workflow addresses the communication of predicted flood depths, flood hazard maps, and coastal erosion hazard zones made in element 4. Common methods include tables with flood elevations by location based on transects or cross sections, maps with discrete flood zones or graduated risk zones based on probability and wave heights, and maps that depict long-term erosion areas or probabilities of erosion. Mapping of current flood zones is necessary for community-based regulatory and floodplain management decisions. Zones or probabilities of erosion hazards are needed for longer-term beachfront management decisions. The outcomes of the coastal workflow are to identify future flood and erosion hazards to provide a projection of future coastal hazards.

One of the most well-known mapping products depicting flood hazards are FEMA FIRMS, which provide specific flood zones and BFEs. The following paragraphs describe the coastal components of these maps as a reference (see Box C for additional information).

FEMA coastal BFEs include a number of drivers related to coastal flooding. Flood hazard studies are considered coastal studies when the flooding being evaluated is a combination of elevated water levels, typically due to storm surge and wave action. Methodologies for developing coastal flood hazard elevations vary by drivers and geographic areas. Coastal flood hazards along the Atlantic and Gulf are associated with large coastal storms and storm surge derived from both tropical and extratropical storms. The dominant coastal flood hazards differ substantially for the Pacific Coast from those on the Atlantic and Gulf coasts. The narrow continental shelves of the Pacific Coast preclude storm surges greater than a few feet, and coastal flood hazards are associated with large waves with long periods. Coastal flooding in the Great Lakes can arise due to elevated stillwater level and/or storm waves, with energetic storm waves occurring concurrently with elevated water levels.

Regardless of geographic area, FEMA BFEs include the assessment of 1-percent-annual-chance stillwater (storm surge and wave setup) coastal flooding, wave assessments (wave setup and runup, overtopping, overland wave modeling), coastal episodic (storm-induced) erosion, and, if applicable, the delineation of a Primary Frontal Dune. The BFE represents an elevation that includes contributions from all of these assessments. For example, the BFE in an area influenced by overland wave propagation will include contributions from the stillwater, wave setup, and the component of the overland wave height that contributes to the total water level. In an area where runup is the dominant coastal hazard process, the BFE will be the 2-percent-annual-chance wave runup elevation. Methodologies associated with the development of coastal flood hazard data can be found through FEMA (2022b) guidance.

*Box C. FEMA Coastal FIRMs BFE Zones*

Current FEMA mapping represents a static view of flood hazard for current conditions and does not provide information on future conditions. Coastal flood BFEs are mapped in terms of zones VE, AE, AH, AO, and X on a FIRM. In addition, the Limit of Moderate Wave Action is typically identified. VE zones are coastal high-hazard areas where wave action and/or high-velocity water can cause structural damage during the 1-percent-annual-chance flood.

VE Zones are identified using criteria for the 1-percent-annual-chance flood conditions based on the following assessments:

- Breaking wave height zone for overland wave propagation
- Primary Frontal Dune zone
- Wave runup zone
- Wave overtopping splash zone
- High velocity zone (landward of the overtopping splash zone)

AE Zones are areas of inundation by the 1-percent-annual-chance flood, including areas with wave heights less than 3.0 ft and runup elevations less than 3.0 ft.

AH Zones are areas of shallow flooding or ponding.

AO Zones are areas of sheet-flow shallow flooding, or where the potential runup is less than 3 feet above an overtopped barrier. The barrier of A zones represents the limits of the Special Flood Hazard Area. Outside of the Special Flood Hazard Area, the 0.2-percent-annual-chance stillwater value can be mapped as a shaded X zone. Additional data may be available from FEMA coastal studies, such as stillwater depth grids and multi-frequency stillwater raster data. Information on the methods used to develop mapping products can be found in FEMA (2021a) mapping guidance documents.

Examples of some existing mapping products depicting erosion hazards are available via the USGS (2017) Coastal Change Hazards Portal. Historical shoreline positions, short- and long-term shoreline change maps, vulnerability maps, and future change forecasts and response likelihoods are available. In addition, many State coastal management agencies monitor coastal erosion and map long-term accretion and erosion rates, which are used to determine regulatory baselines and setbacks.

## B. Advances in Understanding and Actionable Science

Since the 2015 CISA Appendix was written, the Fourth National Climate Assessment (NCA4) has been conducted with updated actionable science, and newer science is available that will be included as input to NCA5 by 2023. Included in the updated science is a better understanding of relative SLR based on regional influences of oceanographic currents, ice sheet fingerprinting, and VLM, as well as improved historical trend analysis and extrapolations out to 2050. The result is the availability of updated SLR scenarios that enable a risk management approach to future flood risk. In addition, more robust process-based coastal modeling is now available that includes the increase in SLR as part of the dynamic modeling input, thus accounting for nonstationarity/non-linear responses (for example, wave runup, which impacts Zone V areas). Also, there are better methods for accounting for special regional considerations, such as for the Great Lakes and in Alaska, that can be included in the analysis. This section describes these changes as they relate to the 2015 CISA Appendix and provides recommended changes and justification for doing so. These developments also motivated many revisions to the FEMA Technical Mapping Advisory Council (TMAC) 2015 recommendations and sub-recommendations and subsequent annual reports (TMAC 2022) and recommendations, including Future Conditions Recommendations FC-3 and FC-7.

### *Project Horizon and Key Project Details*

The diverse purposes and needs associated with Federal actions and projects provide the primary impetus for determining the appropriate, associated, and actionable temporal period. The actual period might depend on the design standards directing the service life of a project. For example, highway bridge design standards apply a service life of 75 to 100 years (American Association of State Highway and Transportation Officials 2020). The associated project horizon would correspond to capturing projections to 2120. Different considerations may align the project horizon with some risk or consequence of failure; for example, an evacuation route might necessitate a longer horizon than a secondary roadway.

### *Element 2b: Future Changes in Climate or Other Environmental Drivers and Evaluation of Sea and Lake Level Projections and Future Wave Climatology*

Observations and models that support dynamic flood modeling are increasingly available and continue to improve. As sea levels change, tidal and other coastal process dynamics will also change, creating a challenge to integrate subaerial and subaqueous landscape change. For example, flood and ebb tides may change in magnitude, causing more intense currents and thus erosion (Passeri et al. 2016). Statistical methods are further being explored and utilized (e.g., Bayesian probabilistic models) to better predict changes over time with a host of initial inputs that can vary over time (Lentz et al. 2016; Lentz et al. 2021; Plant et al. 2016). Dune heights and tidal hydraulics are known to be impacted by changes in sea level. Coupling historical shoreline change rates to SLR and coastal morphology has also resulted in correlations between dune height and erosion rates (Plant et al. 2016). Machine learning and physics-based models (Delft3D and XBeach) have been used to show that SLR and geomorphic change will also impact future habitat and migration of barrier islands. These models enable many different scenarios to be run with varying inputs (Enwright et al. 2021), allowing researchers to change parameters to determine which ones are most important for impacting habitat and erosion and helping to guide decision making for using natural and nature-based barrier island restoration techniques.

### *Mean Sea Level Rise*

Two new, major, authoritative global and regional SLR assessments have been published since 2015, which are the basis for mean SLR guidance under this 2023 CISA Report. Sweet et al. (2017) provided regional SLR projections for the United States for the first time on a 1-degree grid and at tide gauges. In addition, these projections were given exceedance probabilities associated with the Representative Concentration Pathways (RCPs) to assist with determining more likely scenarios. Sweet et al. (2022) updates the global mean SLR scenarios from Sweet et al. (2017) using output drawn directly from IPCC AR6. The underlying SLR science reported in AR6 is also used to calculate exceedance probabilities for each Sweet et al. (2022) global mean SLR scenario around the shared socioeconomic pathways (SSPs), global mean temperature targets, and the inclusion (or not) of lower-confidence ice sheet processes in the model-derived AR6 SLR projections (Working Group 1 2021; Working Group II 2022; Working Group III 2022).

The report updates previous reports (Parris et al. 2012; Sweet et al. 2017) and gives actionable new data for use in coastal flooding analysis.

- **Sea level along the U.S. coastline is projected to rise**, on average, 10–12 inches (0.25–0.30 meters) in the next 30 years (2020–2050), which will be as much as the rise measured over the last 100 years (1920–2020). SLR will vary regionally along U.S. coasts because of changes in both land and ocean height (Sweet et al. 2017).

- **SLR will create a profound shift in coastal flooding over the next 30 years** by causing tide and storm surge heights to increase and reach further inland. By 2050, "moderate" (typically damaging) flooding is expected to occur, on average, more than 10 times as often as it does today, and can be intensified by local factors (Sweet et al. 2022).

The report and accompanying datasets provide:

- Updated global and regional SLR scenarios from today to 2150 by decade for all U.S. States and Territories, including exceedance probabilities across a wide range of scenarios of GHG emissions, associated future climate warming, and the potential contributions from physical processes associated with rapid ice sheet melting for which the IPCC has indicated lower confidence (but which could lead to large and rapid increases in global mean sea level);

- Extrapolated regional sets of tide gauge and satellite altimetry observations (since 1993) from the last 50 years (1970–2020) to project SLR out to 2050 and regionally-averaged projections for 11 different regions around the United States and Minor Outlying Islands (defined in Fig. A1.1 of Sweet at al. (2022)); and

- A new set of extreme water level probabilities to assess coastal flood exposure today and out to 2050 for all U.S. States and Territories.

Federal agencies should apply this latest interagency Federal guidance for regionally-based SLR projections. Scenarios and time horizons should use a consistent national approach based on risk tolerance and criticality. The regional scenarios, based on the appropriate scenario at the closest tide gauge location or 1-degree grid, should be combined with the coastal hazard projection workflow using methods appropriate to policies, practices, criticality, and consequences. Agencies should be aware that updates to the scenarios will continue to be made through the Interagency

SLR Task Force process, in partnership with the NCA. Each agency should factor projected regional/local sea level change into Federal investment decisions located as far inland as the extent of estimated tidal influence, now and in the future, using the most appropriate methods for the scale and consequence of the decision. Using the regional SLR scenarios will account for regional differences based on VLM, oceanographic processes, and ice sheet fingerprinting.

In addition, Federal agencies should use the extrapolated regional tide gauge observations to inform SLR scenario selections for time periods out to 2050, as well as the extreme water level probabilities to inform stillwater and wave effects analysis over that time horizon. For longer-term scenario needs, out to 2150, Federal agencies should use the model-generated scenarios from the Task Force report appropriate for the given risk tolerance and other critical aspects of the decision context, as discussed below.

For "near term" (out to 2050), the scientific advancements captured in the new SLR Task Force report (Sweet et al. 2022) provide an opportunity to recommend a single consensus projection (with appropriate margin of error/safety) for each region/tide gauge/grid cell based on a combination of (a) the observational extrapolation curves and (b) the model scenarios that bound those curves for that particular region/location. A further refinement of this would be to create an "equivalent freeboard" table for each location associated with that single consensus projection. For "long-term" (beyond 2050), agencies can adopt an approach articulated in both Sweet et al. (2017) and Sweet et al. (2022) about using at least two scenarios to ensure that lower probability but high-impact SLR futures are considered in the planning process.

The updated scenarios in the report are grounded in the principles of risk-based framing for climate assessment (King et al. 2015; Weaver et al. 2017; Sutton 2019; Kopp et al. 2019) and are consistent with adaptation pathways approaches for long-term planning that help a community plan for a range of uncertain futures while only investing in adaptation strategies when necessary (e.g., Haasnoot et al. 2013; Bloemen et al. 2018; Hall et al. 2019; Werners et al. 2021). They provide screening-level (suitable for first-order assessment) products appropriate for framing and bounding important Federal investment projects and coastal risk assessment and management. The extrapolations out to 2050, and associated model-derived curves, provide planning scenarios intended to frame near- to mid-term decision contexts and/or longer-term decisions with high-risk tolerance or ability to adjust plans, which address the question of what is most likely to happen. The projections out to 2100 and 2150 provide bounding scenarios designed to set the envelope of possible future outcomes, which can be used to stress-test long-term objectives, gauge the "when, not if" a given level of SLR might be reached, and address the question, "How bad could things get?"

For short-term actions (~30 years to 2050), agencies should use the extrapolated trends in 2050, and then choose the SLR scenario curve immediately above the observational extrapolation to account for uncertainty, as follows:

- For a given location (tide gauge or grid cell), select the regional tide gauge extrapolation associated with that location (i.e., the region that the tide gauge/grid cell falls within).
- Identify the local (for the tide gauge/grid cell) model-derived scenario (e.g., Low, Intermediate Low, Intermediate, Intermediate High, High).
- That particular local model-derived scenario then becomes the planning curve or equivalent freeboard for the upcoming 30-year time horizon.

- If more accurate VLM rates are available or if VLM rates at the tide gauge closest to the action are more appropriate, then they should be applied.

For example, for a Federal action near Savannah, GA (which falls in the Southeast Coast region) with short-term design requirements, the Southeast Coast region is the most appropriate extrapolation to use. The extrapolated Southeast Coast region observation out to 2050 is 1.34 ft. This value is between the Intermediate and Intermediate-High scenarios. Agencies should choose the scenario higher than the extrapolation, in this case the Intermediate-High scenario (1.40 ft).

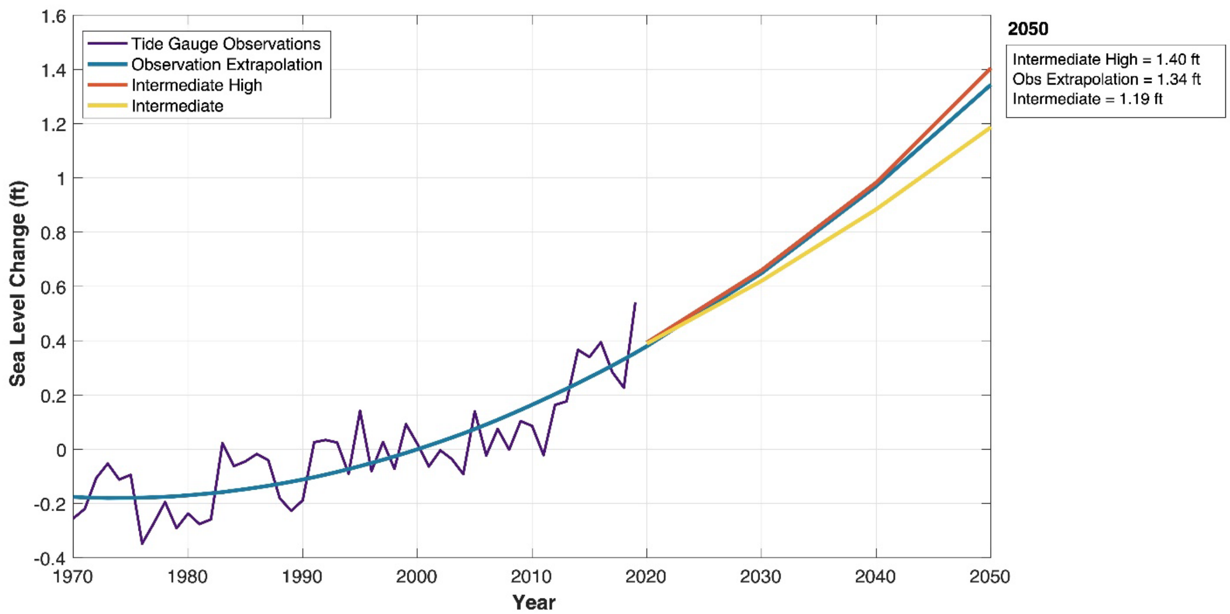


*Figure 4: Southeast Coast regional extrapolated observation to 2050 (NASA 2022)*

With Figure 4 above, agencies should use the scenario higher than the extrapolated value at 2050 for short-term (~30-year actions). In this case, this is the Intermediate-High (1.40 ft) scenario.

If planning and designing beyond 2050, agencies should, when possible, choose at least two planning scenarios to accommodate different risk tolerances. For highly critical actions, a higher than observational extrapolation scenario should be used. Using the previous example, if the same Federal action in Savannah, GA has a much longer design life (2080 [~60] years is used in this example but depending on service life, longer time frames may be considered out to 2150), agencies would use the same higher scenario curve selected at 2050 (in this case the Intermediate-High scenario) at 2080 (3.40 ft) for critical actions and the scenario lower than the extrapolation at 2050 (in this case the Intermediate scenario) at 2080 (2.41 ft) for non-critical actions. The purpose of using at least two scenarios is to make sure agencies are addressing potential low-probability, high-impact plausible outcomes for more critical actions that cannot fail, and higher-probability, lower-impact outcomes for less critical actions with lower consequences upon failure. This strategy will reduce potential overdesign consequences and give agencies the flexibility to decide which scenario is best, based on agency methods for determining the scale and consequence of the action.

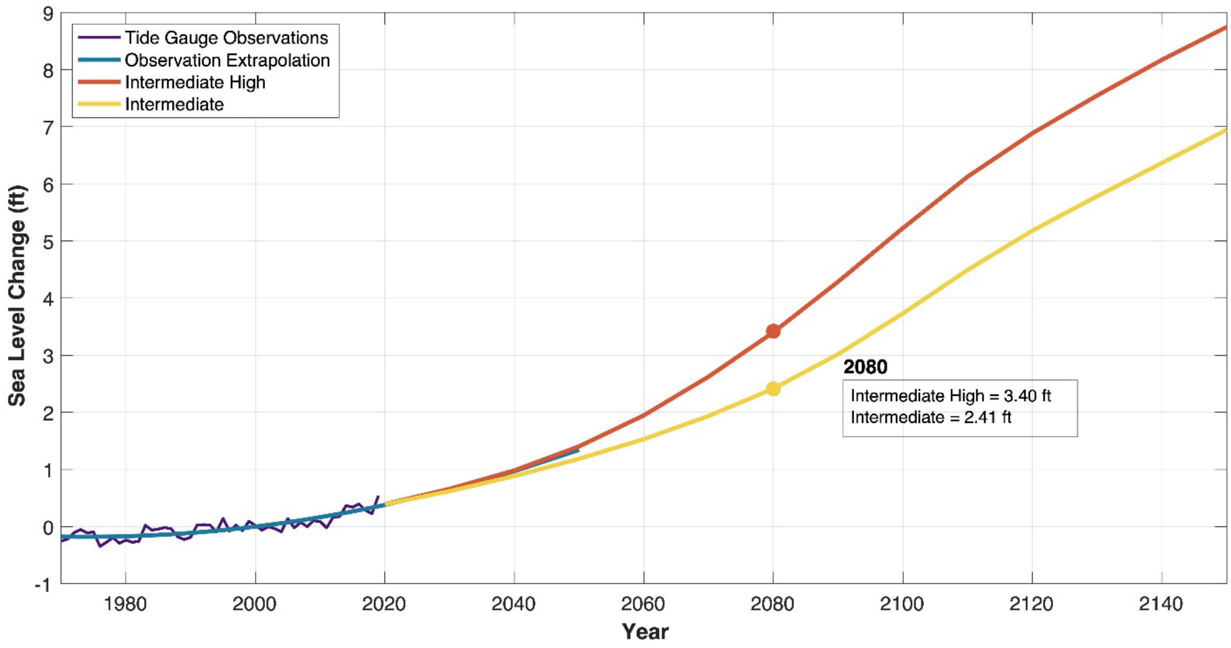


*Figure 5: Southeast Coast regional extrapolated observations to 2050 and scenarios out to 2100 (NASA 2022)*

With reference to Figure 5 above, agencies should use the same higher scenario curve selected at 2050 (in this case the Intermediate-High scenario) at 2080 (3.40 ft) for critical actions and the scenario lower than the extrapolation at 2050 (in this case the Intermediate scenario) at 2080 (2.41 ft) for non-critical actions.

The 2015 CISA Appendix gives agencies options to use other sea level scenario curves that meet peer review criteria. Examples such as USACE SLR scenarios are outlined in the 2015 CISA Appendix, as are criteria defining appropriate scenarios. Upon deciding what scenarios to use, agencies should consider the following:

- Ideally, the presented guidance (and simplified data products and tools) provided in this workflow for using the Sweet et al. (2022) projections/scenarios is simple enough that it incentivizes agencies using them off the shelf, instead of coming up with a custom method.
- There are other Federal- and State-level SLR scenario planning approaches. Using locally derived scenarios based on more local data (e.g., VLM rates) is appropriate as long as they meet the 2015 CISA Appendix criteria.
- Custom approaches might be subject to extra scrutiny, especially if they lead to less protection than the consensus Federal approach.

### *Great Lakes*

The 2015 CISA Appendix stated that in 2015 there was too much uncertainty in projections of future Great Lakes water levels to support guidance to add or subtract freeboard to current flood risk elevations along their shoreline. More information is now available on changing lake levels, and guidance now exists. Borrowing from the NCA 4 (Reidmiller et al. 2018), the following is an update on Great Lakes water-level science.

Great Lakes surface temperatures are increasing, lake ice cover is declining, the seasonal stratification of temperatures in the lakes is occurring earlier in the year, and summer evaporation rates are increasing. Water levels in the Great Lakes fluctuate naturally, though levels more likely than not will decline with the changing climate. A period of low water levels persisted from 1998 to early 2013, likely due to a single warm winter in 1997–1998 (corresponding to a major El Niño event) and ongoing increases in sunlight reaching the lake surface (due to reduced cloud cover). Water levels rose rapidly after 2013: between January 2013 and December 2014, Lake Superior's water rose by about 2 feet (0.6 meters) and Lakes Michigan and Huron rose by about 3.3 feet (1.0 meter). Record-high levels were recorded in Lake Ontario in 2019. Recent projections using updated methods of lake levels for the next several decades under 64 global model-based climate change simulations on average show small drops in water levels over the 21st century (approximately 6 inches for Lakes Michigan and Huron and less for the other lakes), with a wide range of uncertainty.

Because of the more recent variability in water levels in the Great Lakes, flooding and coastal erosion have become more prevalent (Theuerkauf et al. 2019). As higher water levels generally worsen coastal flooding, it is important for agencies to include higher water scenarios when working through the coastal workflow. Therefore, each agency should construct or use a scenario approach for modeling high- and low-water level conditions in the Great Lakes to determine future flood hazard changes.

#### *Alaska*

Unique considerations for employing CISA in Alaska arise from notable limitations in data availability, geographic isolation from many national modeling efforts, and an outsized role of sea ice and VLM in flood risk assessments. When the 2015 CISA Appendix was developed, there was minimal actionable science to inform guidance for Alaska and areas sharing its characteristics. Guidance is provided here in the interest of enabling CISA adoption in areas not fully suited to national workflow considerations.

Alaska experiences extreme changes in regional vertical land level, which include rapid seismic displacement events; multi-year non-linear change associated with post-seismic adjustment; decadal uplift associated with the loss of terrestrial glacial ice mass; and areas of subsidence due to deltaic and volcanic mass loading. At a more local scale, changes in permafrost extent contribute to highly non-uniform ground subsidence patterns. Recent gridded sea level projections capture some of the long-term regional land motion, but analysts are encouraged to augment or validate these trends with assessments of local VLM, when possible, at areas of interest. Location-specific VLM data may be obtained from repeat surveys on benchmarks, from observed motion at Continuously Operating Reference Stations, or from InSAR surveys. In tectonically active areas, any record of past vertical displacement events should be calculated into added factors of safety in design elevations.

### ***Element 3a: Geomorphic Change***

As described in Section III. Assessing Future Coastal Flooding A. Coastal Workflow, resources are available to aid agencies needing to assess the severity of LTCE hazards along U.S. shorelines; however, the spatial and temporal resolution may not be sufficient to support detailed (i.e., parcel-scale, timescales of years to a decade) assessment. The national and international community of coastal researchers and analysts have understood the need to incorporate the impact of physical processes that drive LTCE in the assessment and predictions that are used to manage flooding at Federal, State, and local levels (Elko et al. 2015). These processes include SLR, as well as changes in sediment supply, ecological feedbacks, and human activity, both in terms of restoration and coastal protection. Specific research areas that were identified for investment included: (1) What are the most important factors influencing long-term sediment budgets?; (2) What are the feedbacks and interactions between processes at short time-scales, such as storms, and long time-scales, such as SLR?; (3) How can useful models of LTCE be developed from models that resolve short timescale processes?; and (4) What drives human interventions, how do mitigation strategies coupled with natural processes, impact system dynamics and long-term sustainability, and how might these factors evolve as physical, economic, and policy changes?

Thus, at the time the 2015 CISA Appendix was written, the scientific community had not developed consensus and minimum standards on nationally consistent ways to integrate LTCE and SLR into modeling of coastal flood hazards and coastal floodplain mapping. Since 2015, several pilot studies (outlined in the TMAC 2022 Annual Report) have included approaches for combining analysis of SLR and LTCE with flooding in the context of FEMA's coastal flood study process. In addition, non-traditional datasets such as satellite shoreline measurements are now available. Minimum standards for providing two shoreline scenarios (extreme shoreline excursions and daily conditions) are now needed, as well as secured funding for national LTCE monitoring for periodic updates. While more research is needed before prescribing national guidelines that quantitatively account for geomorphic changes, agencies should encourage efforts that take them into account in locally appropriate ways.

Geomorphic changes that include SLR and storms have advanced to the point where they are included in some publicly available projections of future flood hazards (Barnard et al. 2019; USGS 2021; Passeri et al. 2021; USACE 2015). These current approaches, typically implemented locally or regionally and used for targeted decision-support related to restoration and hazard mitigation, can be used as guidance on which methods to use to determine the impacts on the current BFEs over time. For example, consistent with the TMAC 2021 Annual Report (TMAC 2022) recommendations, recent approaches have incorporated multiple storm and SLR scenarios to forecast future shoreline position and other forms of LTCE relevant to future conditions flood hazards. Different methods, including statistical parameterizations, data assimilation, and numerical process simulations can be evaluated for different coastal settings. The impact of restoration and coastal protection measures can be evaluated by comparing predicted LTCE with and without these projects (Mickey et al. 2020), e.g., comparing a case where the shoreline is restricted from eroding past existing infrastructure (e.g., revetments, seawalls, roads) versus another in which the shoreline erodes without infrastructure restrictions.

#### *Geomorphic Change Observations*

New advances in aerial and satellite imagery have been used to detect volume changes after coastal storm events, including dune movement and overwash deposits. These methods can be used to assess storm impacts and possibly to determine shoreline positions using remote sensing (Sherwood et al. 2018). Overall, higher SLR increases the probability of shoreline erosion (Gutierrez et al. 2011) and many coastal landscapes can respond and adapt over time to sea level change. Static SLR models that do not account for coastal morphology tend to overpredict inundation. Simpler land types such as beaches have more predictable responses, while more complex land types that include vegetation are more difficult to understand (Lentz et al. 2016). Lately, more complex and realistic wave forcings can be modeled over time as well using new methods for downscaling future climate models (CMIP6) to simulate stochastic wave processes over long morphological time scales. These methods more accurately reflect wave impact to morphology over climate time scales (Vitousek et al. 2021).

### *Element 4: Wave Effects*

The new generation of climate models, CMIP6, are now available as part of IPCC AR6, including potential changing wave climatology in the future. There is ongoing research to use these data to project future wave energy that could then be used for modeling. Ongoing research and development in integrating these projected wave models continues. This implementation can be coupled in systems for wave setup in terms of the stillwater elevations. Future wave projections can be included in assessments (e.g., USGS 2021; Barnard et al. 2019). The integration of processes like runup, overland waves, and overtopping require project-based understanding of the drivers and criticality of the project.

Wave effects are an important driver, namely in terms of driving the consideration of coastal high-hazard zones. As discussed, FEMA considers these effects in coastal mapping in terms of wave setup, overland waves, runup, and overtopping (Figure 6).

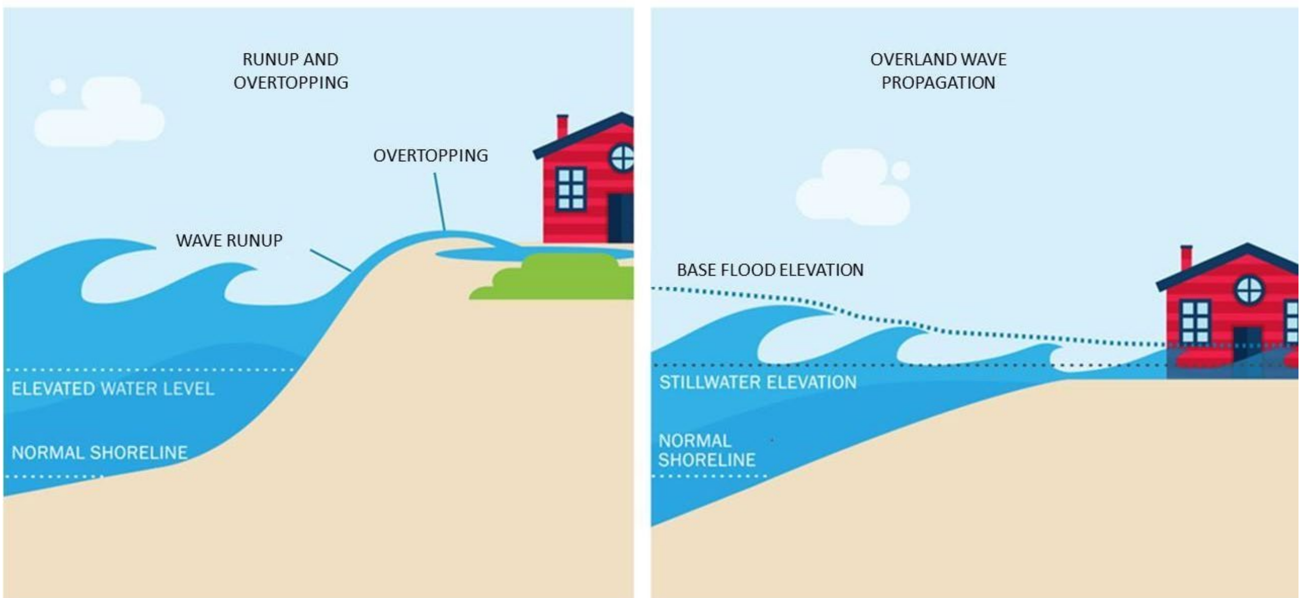


*Figure 6: Overland wave propagation, runup, and overtopping hazards can be modeled to evaluate their risks and to determine BFEs (Mississippi Coastal Map Revision Project n.d., with modifications)*

The 2015 CISA Appendix recommends using a combination of the lowest relative sea level (RSL) conditions with surge, tide, and wave data using state-of-the-art science in a manner appropriate to policies, practices, criticality, and consequences, and there is no actionable guidance to warrant a change in this approach. Notably, areas subject to runup and overtopping can be very sensitive to changes in water level (including due to SLR) and the variability of the slope—so within a CISA implementation, these areas should be treated with appropriate analysis and not simple linear addition of flooding components.

When considering potential future land use changes, these should be integrated based on project-specific conditions. Overland waves can be particularly sensitive to changes in land use. In the overland wave analysis for FEMA studies, this is captured through variability in the cards within the transect-based 1D model, Wave Height Analysis for Flood Insurance Studies (WHAFIS) model.

### *Element 5: Data Sharing and Visualization of Coastal Flood Hazard Information*

Since the 2015 CISA Appendix was developed, new studies have been conducted to evaluate and map the impacts of SLR and long-term erosion on the future BFEs. For example, FEMA conducted two pilot studies following Future Conditions recommendations from the TMAC (2015) Future Conditions Modeling Report that provided prototype maps to visualize erosion areas. Both are summarized in the TMAC 2021 Annual Report (TMAC 2022):

The Nantucket pilot investigated future coastal erosion caused by sea level rise and produced future coastal erosion hazard maps (FEMA n.d.). The study mapped future coastal erosion hazard areas for several specific timeframes: 2030, 2050, and 2100.

The San Francisco pilot found that future changes to the coastal floodplain will result from both the vertical increase in BFEs due to SLR and the horizontal increase in the landward extent of the floodplain due to future shoreline change (BakerAECOM 2016). Maps were developed using a GIS-based buffering technique, which was found to be a viable method to efficiently map future floodplain limits and produce geospatial datasets.

In both cases, the pilots presented methods on how to quantify and map future coastal erosion and SLR-impacted areas (coastal erosion hazard maps) in addition to traditional FEMA flood zones (flood hazard maps). Both in the TMAC recommendations and in the pilot studies, future coastal erosion hazards are intended to be initially mapped and provided as shaded X zones that can help inform coastal/beachfront and floodplain management decisions.

Other example projects include the North Atlantic Coast Comprehensive Study (NACCS), completed in the aftermath of Hurricane Sandy to help Northeastern and Mid-Atlantic coastal communities better understand and prepare for changing coastal flood risks. Completed in 2015, this two-year effort provided technical analyses and tools to help understand coastal hazards and vulnerability. The NACCS also outlined a nine-step Coastal Storm Risk Management Framework for communities to use to inform future coastal resilience efforts (USACE 2015).

Building off the momentum from the NACCS, USACE completed the South Atlantic Coastal Study in 2021. The study effort provided similar technical products for South Atlantic and Gulf Coast coastal communities, including Puerto Rico and the U.S. Virgin Islands. Both studies have been successful in quantifying and communicating future coastal risks associated with climate change and sea level rise (USACE 2021).

Together, flood hazard maps and coastal erosion hazard maps can be used as overlays in GIS systems/maps to inform CISA coastal hazard protection.

## C. Roadmap: Needs and Opportunities to Improve Projections

To improve the coastal workflow process overall and the various data and modeling elements within requires the ability to (a) maintain up-to-date coastal topography and bathymetry, geodetic control, and land cover change, and (b) make skillful statements of past climatology and future conditions of SLR, lake levels, VLM, wave conditions, and ice cover.

### Element 2b: Future Changes in Climate or Other Environmental Drivers and Evaluation of Sea and Lake Level Projections and Future Wave Climatology

#### *Mean SLR*

Continuously tracking how and why sea level is changing is an important part of informing plans for adaptation. The ability to monitor and understand the individual factors that contribute to SLR allows tracking sea level changes to occur in ways that have never before been possible (e.g., using satellites to track global ocean levels and ice sheet thickness). Ongoing and expanded monitoring will be critical as sea levels continue to rise.

- For the near-term, continue to collect and use observations to improve extrapolations and their relationship to modeled projections. Uncertainties in how well regional differences in mean sea level (MSL) across different U.S. regions can be resolved should be reduced. Better spatial and temporal vertical land motion rates are needed to refine local SLR projections.
- For the long-term, it will be necessary to continue to better constrain models with respect to ice sheet processes and to reduce uncertainties with respect to climate-drive shifts in ocean circulation patterns that contribute to SLR differences.
- Create an SLR increment table for regional extrapolated observations associated with the consensus projections selected for the near term (2050).

#### *Great Lakes*

- Reduce the uncertainty in how climate change will translate to water level impacts on the Great Lakes.
- Further develop a basis for understanding how climate change has impacted water levels through attribution studies that build a narrative.
- Improve regional climate modeling by incorporating better representation of the Great Lakes and their influence using 3D lake models.

#### *Alaska*

Alaska's data paucity and geographic isolation from many national marine and coastal modeling efforts create added barriers to assessing changes in significant wave height and extreme water levels associated with the CISA coastal workflow. The added role of changes in the extent and composition of sea ice are an important consideration in assessing coastal flood risk, but future research is needed to incorporate future sea ice projections into scenarios and guidance.

### Element 3a: Geomorphic Change

Coastal morphology is a result of many complex processes over both short and long timescales and small and large spatial scales. The morphology is the foundation for diverse landscapes and land uses, including human activities that require advances in a broad range of data and modeling approaches to determine their potential impact on flood-hazard changes. The roadmap to providing more information associated with geomorphic change includes:

- Develop, expand application, and utilize diverse data sources for assessing LTCE. Shorelines extracted from imagery (including fixed camera, airborne, and satellite platforms), LiDAR, and radar are available at variable sampling rates and spatial resolutions. Sustaining these measurements will resolve more physical processes, and provide more reliable updates and projections. Blending data from historic, current, and emerging observational technologies will ensure resolution of both long-term and short-term processes, and ensure applications to diverse coastal environments (e.g., beaches, cliffs, wetland, permafrost, and VLM).

- Develop, expand, and utilize integrated models to include effects from, and impacts to, landscape response, including natural and human systems. Continuing to advance the geomorphic change forecasting models, driven by climate and weather scenarios to include SLR at both long and short timescales, will support flooding and other impact assessments on infrastructure and habitats. The ongoing development of geomorphological models have varying levels of validation that can vary significantly depending on the region or model type. More uniform validation criteria can help facilitate comparisons between models and techniques and can account for uncertainty and sensitivity (Montaño et al. 2020).

### *Element 4: Wave Effects*

Wave effects are an important driver for identification of high-hazard areas. The roadmap to providing more information associated with this future driver includes:

- Ongoing research into the direct integration of waves into coastal flood analyses.

- In the short term, develop and provide metrics and guidance associated with a qualitative or semi-quantitative estimation of future overland wave conditions to better inform the estimation of future high-hazard areas. The FEMA pilot studies referenced earlier investigated a number of ways to implement this approach.

- In the longer term, utilize direct analysis and a scenario-based approach to provide comprehensive future conditions related to wave hazards with the incorporation of all wave-induced hazard conditions.

### *Element 5: Data Sharing and Visualization of Coastal Flood Hazard Information*

Most agencies currently use Digital FIRMs (DFIRMs) to determine if a Federal action will be inside the current 1-percent-annual-chance floodplain. Based on EO 11988 as amended by EO 13690, agencies are to avoid building within the present floodplain unless another site would be impracticable and, if building within the floodplain, ensure investments are built to be resilient against flooding of this magnitude. To comply with the FFRMS, agencies will need future conditions floodplain maps to determine if Federal actions will be vulnerable to future flooding. Agencies will need information on both the future vertical flood elevation as well as the corresponding horizontal extent of the floodplain.

When the FFRMS was first issued in 2015, national mapping of the FFRMS floodplain did not exist except where 0.2PFA data were already available. This is still the case, and mapping of all FFRMS approaches are needed by Federal agencies, particularly those looking to project and manage future flooding as illuminated through the CISA. In addition to the process of determining the future coastal floodplain, maps similar to DFIRMs are needed for consistent application of the FFRMS.

As FEMA transitions to a risk-informed NFIP, through initiatives such as the program's updated pricing methodology (Risk Rating 2.0), explorations to update modeling approaches to incorporate climate impacts like those underway in FEMA's "The Future of Flood Risk Data" (FFRD) initiative will help meet the Nation's needs for comprehensive hazard and risk data to drive decisions. These explorations follow recommendations from the TMAC. Data potentially produced as part of the FFRD initiative may be able to provide future flood risk information in a probabilistic manner that can inform agencies of not only in-and-out status but also percent likelihood of inundation in the future.

As was mentioned in Section III. Assessing Future Coastal Flooding B. Advances in Understanding and Actionable Science, coastal erosion hazard maps also have a part in the overall CISA coastal hazard protection space. When added to future flood maps (FFRMS floodplain), they could inform erosional hotspots and areas where geomorphologic changes will be a major factor in the evolution of the coastal floodplain.

# IV. Assessing Future Riverine Flooding

This section describes the elements of a future flood hazard-projection process for riverine settings, using the Riverine Workflow (Figure 7) as a conceptual framework for describing the hazard-projection process, to report on new applicable science and to identify a roadmap for bridging science and methodology gaps.

## A. Riverine Workflow

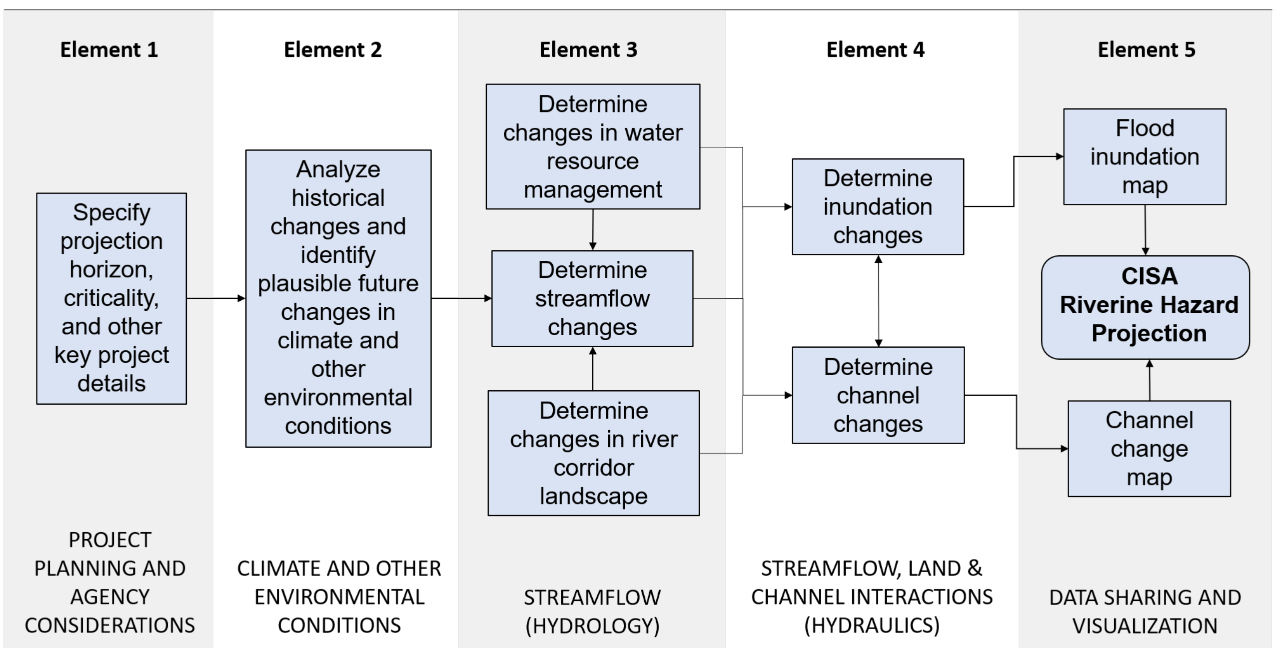


*Figure 7: Workflow for CISA riverine flood analysis.*

Figure 7 summarizes the key conceptual elements for assessing future riverine hazards—flood inundation and channel-related geomorphic change—that agencies should consider when implementing the CISA. Specific considerations for CISA riverine analysis are described in detail below.

The workflow does not identify non-CISA options, but depending on data availability, project criticality, and other project characteristics, the FFRMS permits floodplain definitions other than the CISA, namely the use of the FVA (current 1-percent-annual-chance flood plus either 2 or 3 feet of freeboard depending on whether the action is a critical action) or the 0.2PFA. This section also discusses advances and remaining gaps with respect to these alternatives.

### ***Element 1: Project Planning and Agency Considerations***

There are multiple approaches to modeling most riverine flood and channel change hazards. In addition to project requirements and agency policies, there are unique considerations regarding the availability of data.

#### *Data and Model Availability*

Several factors will weigh heavily in establishing a project-oriented strategy for CISA, including the availability of precipitation or flood peak-flow records and the applicability of a combination of precipitation IDF curves and Bulletin 17C methods for estimating flood frequency at gauged sites (England et al. 2019); data-driven equations for estimating peak flows at ungauged locations (e.g., StreamStats regression equations, Ries et al. 2017); or process-based hydrologic models. Storm rainfall records may be obtained from NOAA (2022). Both the USBR (Sankovich and Caldwell 2011) and the USACE (American Meteorological Society 2020) have compiled data on extreme storms. Instantaneous peak and daily streamflow data, both of which are useful for flood hazard assessments, can be obtained from the National Water Information System. Please refer to the summaries under Element 2 and Element 3 in Section IV.A for more information about data-driven and physics-based modeling alternatives.

Identifying and describing the river corridor is one of the first steps in project planning and is critical for assessing river-corridor change (Warner et al. 2022). Data availability and models for assessing channel change and changes in the river corridor landscape are currently generated at the U.S. State or individual watershed scale. Key data sources for channel-related geomorphic change mapping are currently generated at the U.S. State level and include use of geospatial analytical tools for attributing stream networks with geographic information systems (e.g., Indiana's Fluvial Erosion Hazard Maps; Burke Engineering 2018). State-level data sources include a field or mapping assessment of channel stability and an estimate of bankfull channel width in order to determine a riparian corridor width susceptible to erosion (e.g., Vermont's river corridor erosion hazard zones; Kline and Cahoon 2010). Key data sources for channel-related geomorphic change mapping are currently generated at the U.S. State level and include use of geospatial analytical tools for attributing stream networks with geographic information systems (e.g., Indiana's Fluvial Erosion Hazard Maps; Burke Engineering 2018). State-level data sources include a field or mapping assessment of channel stability and an estimate of bankfull channel width in order to determine a riparian corridor width susceptible to erosion (e.g., Vermont's river corridor erosion hazard zones; Kline and Cahoon 2010).

### ***Element 2: Changes in Climate and Other Environmental Conditions***

Evaluating changes in climate and other environmental conditions is an essential precursor for characterizing current and future floods and associated riverine hazards (e.g., Serinaldi and Kilsby 2015; Schlef et al. 2018). One common challenge with adjusting current and future design floods for climate-driven trends is identifying which components of observed trends can be attributed to sustained long-term changes fueled by rising atmospheric GHG concentrations and which ones arise from multi-decadal oscillations (Jain and Lall 2001), shorter than the intended service life of many projects (e.g., Luke et al. 2017). In other cases, concurrent trends in multiple drivers of flooding, such as climate and land use, may complicate efforts to attribute observed trends and project them forward into the future (Merz et al. 2012; Over et al. 2016). Moreover, data on key drivers of flood trends may not be available, or the effects of concurrently evolving watershed conditions on floods may be confounded, both of which can cause misleading attributions of trends. Complicating matters further, changes in smaller and larger floods may arise from distinct drivers of change (Xiong et al. 2020; Bertola et al. 2021).

Different methods are available for quantifying the effects of climate and watershed change on historical and future flooding. Yet, despite the extensive literature on this topic, there remains a lack of consensus on the best approaches for projecting future flooding in response to anticipated climatic changes (Schlef et al. 2021; Kundzewicz et al. 2016). Approaches for examining the potential effects of climate change on flooding range from empirical approaches based on observed relationships between changes in climate and watershed drivers and floods during recent historical periods (e.g., Schlef et al. 2018; Awasthi et al. 2022) to process-based hydrologic simulations of flood events. These process-based models can simulate individual flood events using design storms based on (i) nonstationary intensity-duration-frequency curves or (ii) historical weather events simulated under different land-surface, oceanic, or atmospheric conditions projected under climate change. In addition, “continuous simulation” process-based models can examine the effects of climate change over periods generally spanning multiple decades, including the impacts of antecedent moisture conditions.

One general advantage of process-based hydrologic simulation modeling of either individual flood events or long-term periods is that it provides a tool with which the sensitivity of flooding to specific climatic or watershed changes can be examined without the confounding effects of unobserved phenomena. However, simulation models often are more costly, have limited representations of physical processes, and struggle to estimate extremes accurately due to the coarse spatiotemporal resolution of input data (e.g., Haddeland et al. 2002; Huang et al. 2019), their limited ability to emulate complex watershed processes, and attenuation biases arising from model smoothing effects (Farmer and Vogel 2016). In addition, similar calibration results may be achieved with distinct combinations of watershed parameters, a.k.a. equifinality, which can make inferences regarding climate impacts more challenging (Her et al. 2019). Moreover, a set of model parameters calibrated under recent watershed conditions may become less suitable under future climate-induced changes to the landscape (Yang et al. 2022).

The choice between modeling flood responses of individual storm events, a.k.a. design storms, versus continuous simulation is also important, as are choices of approaches for representing individual events and future climate sequences. For instance, continuous hydrologic simulation models can examine the flood impacts of historical weather sequences amplified due to expected long-term climatic changes (e.g., Hecht et al. 2022) or simulated future climate time series that are intended to project the evolution of long-term climate properties rather than future flood events. These future time series may be derived from GCMs (e.g., Schlef et al., 2018) or stochastic weather generators (e.g., England et al., 2014; Zhu et al., 2018). Finally, choices of sensitivity analysis methods for analyzing simulation model results, including differences between ones that attempt to isolate the effects of individual variables and ones that aim to identify synergistic effects among different drivers of change (Radke et al. 2020), are important to consider.

In contrast, data-driven approaches, including classic statistical methods and artificial intelligence algorithms, often require fewer data and computational resources and are not constrained by limited quality of process representations of in process-based simulation models. However, they are more vulnerable to misleading attributions arising from confounding and omitted drivers of change. Care must also be taken to select functional relationships that represent physical relations between phenomena well (e.g., Nott et al. 2012). Causal inference methods, such as panel regression (e.g., Over et al. 2016; Blum et al. 2020), can mitigate these pitfalls to some degree (see discussion in Bassiouni et al. 2016 for more details), albeit not to the extent of a controlled watershed experiment. Data-driven approaches also rely upon assumptions that historical relationships between environmental drivers and flooding remain intact over future periods. In addition, data-driven approaches sometimes reveal stronger empirical relations between flooding and underlying variables rather than ones that have more direct impacts on flooding. For example, Schlef et al. (2018) found that geopotential height and soil moisture were better predictors of winter and early spring flooding in the northwestern Ohio River basin than precipitation metrics. Schlef et al. (2021) also find that flood projections based on physically meaningful covariates and GCMs both perform better than ones using extrapolations of observed temporal trends. Extrapolation is valid only when the drivers of the trend (e.g., increased imperviousness) during the historical period are known, future conditions data for the drivers are available for the period of extrapolation, and the empirical relationship between the drivers and flooding can be expected to remain intact through the period of extrapolation (Salas et al. 2018; Serinaldi et al. 2018). Otherwise, apparent trends in recent years may, in fact, be artifacts of interdecadal fluctuations, which can lead to unsound adjustments of design floods (Luke et al. 2017).

In summary, both data-driven and process-based simulation models each have advantages and limitations for elucidating the effects of climatic and watershed drivers of change on flood hazards. Hybrid approaches are also available. For instance, Farmer and Vogel (2016) demonstrated that reintroducing calibration residuals following simulations alleviates attenuation biases in predictions of hydrologic extremes. Relatively few comparisons of these competing approaches have been carried out (see discussion in Section IV. B. Advances in Understanding and Actionable Science Element 3: Streamflow (hydrology) for more details).

The following sections provide more conceptual background for analysis of these potential drivers of change.

### *Climate*

Changes in many climatic indicators, especially precipitation and temperature, have been associated with observed changes in riverine flooding in the United States and elsewhere (e.g., Milly et al. 2008; Frans et al. 2013; Awasthi et al. 2022). Projected climate-driven increases in the frequency and magnitude of riverine flooding in many locations (e.g., Naz et al. 2018; Batibeniz et al. 2020; Neri et al. 2020; Wing et al. 2018; Schlef et al. 2021; Wobus et al. 2021; Mizukami et al. 2022), the ubiquity of increases in extreme precipitation throughout the United States (Wuebbles et al. 2017), decreasing snowpack storage in mountainous regions (Davenport et al. 2020; Dethier et al. 2020), and recently observed increases in flooding in some U.S. regions (Slater et al. 2021; Dethier et al. 2020) all motivate use of the CISA for determining the FFRMS flood elevation and floodplain. Determining the CISA floodplain using the best-available climate science requires the analyst to evaluate the evolution of future flood hazards over the course of a project planning horizon. The main text of this State of the Science report assumes that the CISA floodplain is defined by the maximum water level with a 1-percent-annual chance of occurrence during the year with the most severe flood hazards over a project horizon. In the case of gradually increasing (decreasing) flood hazards, this amounts to the 1-percent-annual-chance flood during the last (first) year of a planning horizon. (See Appendix B for an alternative approach to identifying the CISA floodplain that integrates the full range of flood hazards over the course of a project horizon.)

As previously stated, despite the extensive literature on climate change-driven projections of flooding, there remains a lack of consensus on the best approaches for projecting future flooding in response to anticipated climatic changes (Kundzewicz et al. 2016; Schlef et al. 2021). Approaches for examining the effects of climate change on flooding range from the use of nonstationary design storms to simulate individual flood events arising largely from individual storms to running long-term simulation models forced with synthetic meteorological time series produced with data-driven stochastic weather generators (e.g., England et al. 2014; Zhu et al. 2018) or downscaled and bias-corrected GCM runs. Temperature changes are also important given the extent to which they can affect both evapotranspiration and cryospheric processes (including the fraction of precipitation falling as snow, snowmelt, frozen ground, etc.). In addition to these common variables, many underlying atmospheric conditions, such as oceanic-atmospheric patterns, have demonstrated associations with flooding in some regions (e.g., Jain and Lall 2000; Schlef et al. 2018; Dickinson et al. 2019).

The suitability of these approaches often depends on the strength of relationships between climate variables and flooding in a particular location. For instance, the design storm approach, which assumes a storm with a given exceedance probability generates a flood with an equivalent exceedance probability, tends to perform worse in locations where soil moisture storage is depleted (Ivancic and Shaw 2015; McMillan et al. 2018). Haberlandt and Radtke (2014) evaluated various calibration strategies for using hydrologic models to estimate derived flood frequencies. They concluded that the best representation of the design-storm based flood frequencies is obtained when the hydrological model driven by a design storm with a given annual exceedance probability that is calibrated directly against probability distributions of observed peak flows. This calibration strategy can help ameliorate challenges associated with the fine spatial scales of data and modeling required for high-fidelity simulations of important runoff-generation processes, such as saturation-excess overland flow and variable source-area hydrology (Betson 1964; Dunne et al. 1975).

While best practices for simulating hydrologic impacts of climate change call for selecting climate models whose historical simulations reproduce historical trends in streamflow well (Mohammed et al. 2015), there are inevitably cases in which flood projections using different climate models and/or observed trends do not concord with one another (e.g., Hallegatte et al. 2012; Giuntoli et al. 2021). In some cases, the direction of change may even differ among different GCM-driven simulations of future flooding (Schlef et al. 2021). This does not necessarily mean that all projections are meaningless. Rather, the ensemble of plausible projections may collectively define a range of potential impacts that analysts should consider given their project-specific risk tolerance. When the direction of change in flood hazard is uncertain based on inferences from both climate model-driven hydrologic simulations and observations, the under-design consequences of flooding may warrant a more conservative (higher-elevation) floodplain. In other cases, over-design consequences associated with the investments required for more severe scenarios may warrant defining the current 1-percent-annual-chance floodplain as the CISA floodplain provided there are no other changes in watershed conditions, including the river corridor landscape.

There are some other important considerations in analyzing climate-driven impacts to flood hazards. First, it is important to examine changes in extreme flooding when identifying the CISA floodplain, as trends in large flood events (i.e., those exceeding the flooding that would be expected to occur annually on average) may differ from trends in the full annual maximum instantaneous peak-flow series[13] (Collins et al. 2022). Many contemporary nonstationary flood frequency analysis studies only examine changes in the central tendency of floods, which essentially examine changes in the magnitude of floods expected to occur every two years. A focus on central tendency inhibits efforts to identify places with general drying and warming trends, such as California, that may experience a greater likelihood of catastrophic flooding from atmospheric rivers under warmer temperatures (Huang and Swain 2022). Other recent studies have also suggested increases in the future likelihood of recent catastrophic hurricanes (Lin et al. 2016) whose effects on extreme flooding might be underestimated if only changes in typical annual floods were considered. On the contrary, recent U.S. studies have shown the frequency of flooding above a peak-flood threshold exceeded twice annually on average has been increasing more than the magnitude of larger floods in some regions (Mallakpour and Villarini 2015; Hirsch and Archfield 2015). Importantly, such increases in the frequency of flood events do not necessarily mean that large floods used in infrastructure design, such as the 1-percent-annual-chance flood, are changing.

Second, recent increases in precipitation have not always translated to increases in flooding, especially large floods (Sharma et al. 2018; Hodgkins et al. 2017; Collins et al. 2022). There are many potential reasons for this (Sharma et al. 2018). For example, warmer temperatures may cause lower antecedent (pre-storm) soil moisture, increase infiltration rates, and expedite groundwater recharge, which can, in turn, curtail the flood-magnification impacts of increases in total and extreme precipitation (Sharma et al. 2018). Effects of greater extreme precipitation on flooding may be greater in small headwater basins whose size matches the scale of convective events, whereas flooding in larger basins is much more dependent on the concurrence of extreme precipitation, snowmelt, and soil moisture at seasonal time scales (Blöschl 2022). The seasonality of precipitation increases can also affect the impacts that rising precipitation can have on floods. For instance, Small et al. (2006) suggested that an increase in fall precipitation, a time of year during which greater soil moisture storage is available, also contributes to the lack of increases in flooding from greater rainfall in some regions of the United States.

Differences in the effects of increased precipitation on smaller and larger floods have also been examined. Brunner et al. (2021) posit that projected increases in extreme precipitation may contribute to larger floods more than smaller ones since larger ones are more likely to take place under greater degrees of basin soil saturation. They also recognize that warming-enhanced infiltration may produce greater percent reductions in smaller events than larger ones. However, their study of the German region of Bavaria has not been replicated in the hydrologically diverse regions of the United States. More studies are needed to evaluate how changes in extreme precipitation may affect smaller and larger events differently, including a better understanding of why some U.S. regions (e.g., Northeast) have recently experienced substantial increases in precipitation without increases in large floods.

[13] The annual maximum instantaneous peak-flow series is the highest instantaneous peak discharge in each water year (October 1 - September 30) of record. Practically, this is the highest value observed in the record of 15-minute or 60-minute values, depending on the recording interval of the measuring device. *See* USGS. 2019. "Guidelines for Determining Flood Flow Frequency Bulletin 17C". https://pubs.usgs.gov/tm/04/b05/tm4b5.pdf

However, the lack of flood magnification in response to recent increases in precipitation does not necessarily mean that such a response will continue. Ideally, climate models will be able to reproduce such a lack of changes in large floods in response to rising precipitation and then be able to predict whether such inelastic responses to rising precipitation may continue. When modeled hydrologic responses to climate simulations of historical periods are biased when compared to observations, one general approach that is often plausible is to examine the relative difference between the simulated response during historical and future periods and then apply that change to the observed responses. While observed changes represent an important reference point for assessing future flood hazards, solely considering them prevents future changes in climate, especially historically unprecedented ones, from being taken into consideration in project design. For this reason, it is especially important to consider both observations and simulations when assessing future flood hazards.

Third, in other cases, an increase in precipitation accompanying a warming trend may be, in part, due to long-established patterns of multidecadal variability rather than climate change alone (Todhunter 2012; Huang et al. 2021). It may also be more difficult to distinguish trends attributable to warming in places where multi-decadal variability has been a hallmark feature of the climate for millennia (Cohn and Lins 2005). In fact, many of these multi-decadal oscillations have demonstrated a strong link with flooding in some regions (Jain and Lall 2001; Dickinson et al. 2019). For projects with relatively short service lives, distinguishing between long-term drivers of change and multi-decadal oscillations can be less critical since it is important to project the change over the planning horizon regardless of its origin. However, for projects with longer service lives, short-term changes in flooding driven by climate oscillations may not persist for the duration of the project and increase the likelihood of over-or under-design consequences.

Fourth, some of the most pronounced climate-driven hydrologic changes are projected in cold regions where temperature-driven “cryospheric” processes, i.e., ones involving snow and ice, are an important component of the hydrologic cycle (Brunner et al. 2020; Mizukami et al. 2022). Recent reductions in the fraction of precipitation falling as snow have been associated with observed increases in flooding in the Western United States (Davenport et al. 2020). Dethier et al. (2020) also observed widespread increases in flooding in regions with snowmelt-driven flood regimes despite decreasing snowpack. However, these increases have not been observed or anticipated to be ubiquitous, since warmer winters can also lead to less snowpack and lower spring snowmelt volumes, especially in some parts of the Eastern United States (Ford et al. 2021). Rain-on-snow events, in which radiation, sensible heat, latent heat (condensation) and advective heat transfer accelerate snowpack melting (Li et al. 2019), have become less frequent and smaller in some basins in the Western United States where they have historically been the predominant flood type (Huang et al. 2022). However, simulations of future climate scenarios in the Western United States have found that rain-on-snow events will increase at higher elevations in this region where seasonal snowpacks are expected to persist (Musselman et al. 2018). Warmer temperatures also reduce the extent of permafrost and seasonally frozen ground, which, in turn, can affect soil infiltration and storage capacity and the magnitude and timing of flooding. They also affect glacial melt rates (van Beusekom and Viger 2018) and the frequency and magnitude of glacial lake outburst floods (Harrison et al. 2018).

Finally, ice jams cause annual water-level maxima in many locations in the Northern United States. At some sites, they cause more water-level maxima than annual peak-discharge events and/or have produced some of the highest water levels on record at some locations (FEMA 2018). Thus, changes in the frequency and magnitude of ice jams (see Rokaya et al. 2022 for a review) must be assessed at sites prone to these flood hazards. Many contemporary nonstationary approaches for determining the water level of a flood with a 1-percent-annual-chance in any given year would likely require modifications for use at ice jam-prone locations. Such work would likely involve a mixed-populations approach that considers both open-water and ice-jam events that comprise the annual water-level maxima at a given site (Beltaos 2021). While studies modeling the effects of climate change on ice-jam frequency have emerged (e.g., Rokaya et al. 2019; Turcotte et al. 2020; Lamontagne et al. 2021), a mixed-population-based approach for adjusting design events for changes in the relative frequencies of annual water-level maxima during ice jams and open-water conditions has yet to be demonstrated (see recent reviews by Beltaos, 2021; Rokaya et al., 2022). Future flood projections would also need to recognize that warming does not necessarily lead to a smooth, gradual reduction in ice-jam events at a site (Carr and Vuyovich 2014; Burrell et al. 2022).

#### *Land Use*

Changes in the use, cover, and management of land can all affect riverine flooding. Changes in land use, such as urbanization, often lead to changes in the biophysical properties of land cover, underlying soils, and subsurface drainage that affect the generation and routing of runoff (Leopold 1968). Land and water management practices can ameliorate the flood magnification effects of many changes in land use. For instance, more stringent stormwater regulations have attenuated the flood magnification effects of impervious cover in some U.S. cities (Ntelekos et al. 2010). Excessive extraction of groundwater also contributes to permanent ground subsidence and related ground failures that affect flow regimes and the performance of flood-control structures (e.g. Faunt et al. 2016; see Box B) and can lower floodplain elevations.

As with climate change, a change in land use can be suggestive of a changing flood regime but does not necessarily mean that floods are changing. Even in areas experiencing greatly increased impervious surfaces and associated runoff, channel storage or detention may retain or slow the delivery of that runoff to the watershed outlet, reducing peak flows. Moreover, drivers of change in smaller floods may differ from ones affecting larger floods (Bertola et al. 2021). Some well-studied drivers, such as impervious cover, are known to affect the magnitude of smaller floods more than the larger ones that the FFRMS is targeting (Hollis 1975; Hecht and Vogel 2020). This is especially important since a recent study found that larger floods have changed relatively little in much of the United States (Collins et al. 2022).

Analysts should also evaluate the hydrologic effects of changes in land cover that may result from natural or anthropogenic disturbances, especially wildfires. Wildfires have substantially magnified high and peak flows in fire-prone regions throughout the U.S. (e.g., Neary et al. 2003; Moody 2012; Kinoshita et al. 2014; Brogan et al. 2017; Saxe et al. 2018; Floyd et al. 2019; Beyene et al. 2021; Wagenbrenner et al. 2021) due to their removal of vegetation and production of hydrophobic soils. Relatively few attempts have been made to develop approaches for adjusting peak flows for wildfire impacts at ungauged locations within larger regions (Foltz et al. 2008; Moody 2012). For example, Moody (2012) developed an equation to quantify the effect of severely burned area in a watershed to its runoff response from 30-minute precipitation events based on observations in small watersheds in Colorado and New Mexico. The national flood-frequency guidelines in Bulletin 17C (England et al. 2019) do not provide any recommendations for accounting for wildfire impacts in the computation of design flood events. Flood records cannot easily be bifurcated into fire-impacted and non-fire-impacted periods for use in a mixed-population approach to flood-frequency analysis since the effects of wildfires on peak flow generally recede gradually over time.

Moreover, methods for identifying the termination of periods of fire impact are still in their infancy (Wagenbrenner et al. 2021) and, in some cases, pre-fire vegetation may not become re-established (e.g., Ratajczak et al. 2014). More sophisticated analyses might also consider how climate change impacts on factors such as precipitation and temperature might exacerbate conditions that may promote wildfire hazards, such as flooding (Touma et al. 2022).

### *Element 3: Streamflow (Hydrology)*

The 2015 CISA Appendix did not specify required elements or identify preferred practices for a CISA riverine flood projection workflow, nor are there currently official Federal recommendations for specific methods to consider when adjusting the 1-percent-annual-chance event for changing conditions (i.e., specify a 1-percent-annual-chance peak flow for a given climate or land use status). The recently published Bulletin 17C (England et al. 2019) recognizes the effects that these drivers of change can have on flood frequency but does not prescribe any specific methods for adjusting design peak flows for them. Under these circumstances, agencies have wide latitude and discretion for selection among the many candidate methods. Fortunately, additional community experience and new methodological developments can inform that selection. Section IV. B. Advances in Understanding and Actionable Science describes recent advances in these multiple areas and the way that they complement more traditional approaches to flood modeling, while Section IV. C. Roadmap: Needs and Opportunities to Improve Projections surveys remaining gaps and lays out a roadmap for addressing them.

### *Element 3a: River Corridor Landscape Change (Including Erosion)*

Human- and climate change-caused alterations of streamflow and land cover may trigger rapid, interrelated, and unexpected changes in a river channel's depth, width, and location (Bull 1991; Naylor et al. 2017; Candel et al. 2018). These changes may affect the routing of streamflow during flood events and may mediate the effects that changes in streamflow have on inundation depth. In addition, these changes can result in severe damage and loss of buildings and infrastructure (FEMA 1999). In a study of 401 sites in the conterminous United States, Slater et al. (2015) found that changes in flood hazards due to geomorphic changes were more common, albeit smaller in magnitude, than ones emanating from hydrologic change. This finding corroborates the importance of geomorphic changes to the river corridor on flood hazards and motivates the inclusion of changes to the river corridor landscape into the riverine workflow (Figure 7).

Flood-related geomorphic changes include gullying and upstream channel extension in headwaters, downcutting of channel beds, channel widening, lateral migration, and aggradation (deposition and braiding). These changes can happen throughout a channel network but predicting when and where depends on streamflow, unit stream power (Yochum et al. 2017), and additional interacting factors of slope, channel confinement, and the balance of sediment supply (Lane 1955; Dust and Wohl 2012; Sholtes et al. 2018). Flood frequency characteristics coupled with hydrography, and topology can be used to map river reaches susceptible to landslides, bank failures, and floodplain deposition (Gartner et al. 2015; Yochum et al. 2017; Blazewicz et al. 2020). GIS-based approaches for mapping reaches with river channel change hazards involve mapping river process corridors (Kline and Cahoon 2010; Gartner et al. 2019).

### *Element 3b: Water Resource Management Impacts*

The 2015 interagency implementation guidance for EOs 11988 and 13690 retained the prior (1978) EO 11988 requirements to account for water resource management impacts in floodplain delineations. However, many statistical and process-based hydrologic modeling approaches have a limited ability to account for the effects of water management, including reservoir storage, withdrawals, return flows, and flood barriers. Thus, it is essential for agencies implementing the FFRMS to screen their watersheds for these water management effects on streamflow and determine whether existing models available for estimating extreme peak flows adequately take them into account.

Watersheds subject to active management of flows, such as reservoir releases or water diversions, pose a special challenge for long-term planning. Revisions to operational plans and rule curves are always possible over a lengthy planning horizon, but foreseeable, additional public pressure to deal with expected increases in future flooding or water depletion may drive larger and more widespread adjustments to operations than is currently common with consequential impacts on other agency projects. In addition, climate change adaptation concerns may motivate the construction, expansion, or improvement of infrastructure, such as raising a floodwall or a dam impounding a flood-control reservoir. These sources of important societal feedback must be taken into account when projecting future flood risk.

### *Element 4: Streamflow, Land, and Channel Interactions*

Once the hydrology and discharge are estimated, the next step is to determine the depth associated with these discharges within the riverine system. An important takeaway is that the selection of models, particularly the choice between 1D and 2D models, should be governed by channel conditions and data availability. Olson and Simeone (2021) demonstrated that simulated riverine floodplains predicted by 1D and 2D models need not be significantly different when simplifying hydraulic assumptions apply. However, most riverine systems cannot be characterized as prismatic sections with a constant slope, size, bed roughness and discharge (e.g., an irrigation canal); or, in other words, situations typically described by hydraulic engineers as “steady and uniform” flow. Rather, the shape, slope, bathymetry, bed characteristics, and hydrography of these riverine systems constantly change, both spatially and temporally. To address these changes properly, the dynamically changing shape, slope, bathymetry, bed characteristics, and hydrography of the channels must be considered. As a result, flood depth estimates in riverine systems (including floodplains) must address basic physics, including conservation of mass, energy, and momentum. These physics are well represented in common 1D hydraulic models in limited situations where channels are relatively uniform and simple and where the assumptions underlying the models are valid for the specific riverine setting under study, but they are more usefully represented in 2D hydraulic models—which are more generally applicable than 1D models to the more complex, real-world conditions prevalent in riverine floodplain mapping. Two-dimensional models provide the additional benefit of detailed velocity and depth mapping at a resolution and process fidelity not possible with a 1D model, both of which are important for complex channels and for detecting locations likely subject to channel change. Moreover, preparation of datasets for 2D models may be easier and more cost-effective than preparation of data for 1D models. Advances in multi-dimensional modeling are described in Section IV. B. Advances in Understanding and Actionable Science.

### *Element 5: Data Sharing and Visualization of Riverine Flood Hazard Information*

This final element of the workflow addresses the visualization of predicted inundated areas, flood depths, and extent of erosion hazards made in Element 4 via maps (see Section IV of the report for more on unmapped areas). Currently, FEMA delineates the floodplain and floodway boundaries of the base flood, which corresponds to the elevation inundated with a 1-percent-annual-chance event. Inundation hazards are delineated by finding the intersection of the ground surface defined by the digital terrain model and the flood surface. There are no national standards for mapping geomorphic hazards, including fluvial erosion hazard corridors, though various U.S. States have developed procedures for identifying and mapping them.

FEMA Flood Insurance Studies include an assessment of hydrology and hydraulics at multiple return periods, but do not incorporate nonstationary analysis. Mapped FEMA FIRMs represent the boundaries of areas inundated during floods with 1- and 0.2-percent-annual-chance of exceedance. FEMA (2022b) guidance documents provide information on how hydraulics can be simulated using 1D or 2D methods.

### *Integration Considerations*

The integration of the five elements of this workflow requires some additional considerations, including computational requirements and alignment of spatiotemporal scales, along with the identification and quantification of cascading errors and uncertainty. Since this workflow is essentially a framework, Elements 2–4 of the workflow may feature many different models with widely varying degrees of complexity and, consequently, computational demands. For example, a simpler approach applied to a small watershed with only minor anthropogenic disturbances might be easier to execute on a personal computer. Such an approach could entail a modeling sequence (modeling chain) featuring:

- A statistical model that relates some historical annual climate and land use statistics to peak flows at a site of interest in a small watershed with a geomorphically stable river corridor;
- Projections of future peak flows using this statistical model (assuming out-of-sample validation within historical period) with literature-informed perturbations of historical climate and land use data;
- Negligible geomorphic and water-resources management considerations; and
- A hydraulic model using a design flood hydrograph adjusted for future changes in streamflow using some simplifying assumptions.

In contrast, a much more computationally intensive approach requiring a high-performance computer could feature climate scenarios downscaled from an ensemble of GCMs at a very high spatial (≤ 5 km) and temporal resolution (≤ 1 day) used as inputs into a distributed hydrological simulation model of a large watershed that generates daily or sub-daily hydrographs (e.g., Dullo et al. 2021). These reach-specific hydrographs could then be used as inputs into a coupled geomorphic-hydraulic simulation model that examines the evolution of the river channel over time and predicts inundation (and channel change) during future flood events (e.g. Praskievicz 2015; Tang et al. 2021).

## B. Advances in Understanding and Actionable Science

This section describes advances in climate adaptation planning applications for riverine flood hazards that have been made since 2015, as well as some earlier ones that were not considered in the 2015 CISA Appendix. This section also identifies advances in climate, hydrologic, and hydraulic modeling and reviews their potential application to the characterization and mapping of future conditions flood hazards and risks.

### ***Element 1: Project Planning and Agency Considerations***

The 2015 CISA Appendix emphasized the importance of uncertainty in project planning, as it explicitly stated that "[t]he CISA approach to address future flood risk must incorporate uncertainty." In response to a greater societal demand for climate change adaptation, methods for planning under future climate uncertainty have proliferated in recent years (e.g., Hallegatte et al. 2012; McPhail et al. 2018). This includes a recognition that probabilities often cannot be readily assigned to many projections of future climate and other environmental conditions (Dessai and Hulme 2004) and that the robustness of decisions to plausible scenarios with unspecified probabilities can produce meaningful adaptation guidance (e.g., Herman et al. 2015; McPhail et al. 2018). Section II of the 2015 CISA Appendix also recognizes the value of identifying such plausible scenarios with unknown probabilities and notes that the "CISA approach explicitly accounts for uncertainties through the use of several emission pathway scenarios, multiple Global Circulation Models" and also multiple GCM ensembles. In most planning applications, sets of scenarios defined by these three features are not assigned probabilities.

The 2015 CISA Appendix observed that scientific support for using scenarios for planning in the coastal environment was stronger than it is for addressing riverine flood management. In the course of developing this State of the Science report, the agency authors reviewed developments in project planning in a climate context that have occurred or are underway within multiple agencies and, consistent with the 2015 CISA Appendix, affirmed the importance and value of agencies applying appropriate judgment in their application of CISA. Agencies and their staff have distinct analytical skills and are best aware of the objectives of individual agencies and projects.

### ***Element 2: Changes in Climate and Other Environmental Conditions***

#### *Climate Conditions*

Projections of long-term future riverine flood conditions require projections of future climate, particularly the primary driver of large floods, extreme precipitation, and the primary modulators of flooding, soil moisture storage and evapotranspiration. Traditionally, extreme precipitation-frequency datasets such as NOAA Atlas 14 (Perica 2018) have served as the basis for "design storms" that are fed into hydrologic models to predict peak flows and their associated hydrographs. In addition, computationally intensive simulations of catastrophic historical events under future climate and/or land use conditions have become more widespread in recent years (e.g., Lin et al. 2016; Zhang et al. 2018; Huang and Swain 2022).

In addition to event-scale simulations, future flood projections can be estimated with "continuous simulation" approaches in which complete projected future time series of precipitation and temperature and other meteorological variables are input into hydrologic models. These approaches are especially beneficial for modeling the mediating impacts of antecedent soil moisture and snow conditions on storm runoff. Numerous studies examining climate-change impacts on flood hazards have employed this continuous simulation approach (e.g., Schlef et al. 2021; Dullo et al. 2021; Pal et al. 2022). With continuous simulation models, it is especially important to reintroduce residuals from model calibration into the simulated time series to avoid attenuating extremes (Farmer and Vogel 2016) or to target the accurate simulation of extremes in the calibration process (Majone et al. 2022).

*Precipitation*

The hydrologic impacts of changes in precipitation have been evaluated using either projected daily precipitation time series or projections of changes to IDF curves. There remains a lack of consensus regarding the use of these two methods for projecting future flood hazards. One prominent set of future IDF curves arises from NOAA Atlas 14 curves that express the relationship between precipitation intensity, duration, and frequency for historical conditions.

NOAA's NWS Office of Water Prediction Hydrometeorological Design Studies Center (HDSC) has been updating precipitation frequency estimates for various parts of the United States and affiliated Territories since the early 2000s. Precipitation frequency estimates, with corresponding upper and lower bounds of the 90 percent confidence interval, are produced on a 30 arc-second resolution grid for durations ranging from 5 minutes to 60 days for average recurrence intervals of 1 to 1,000 years. These estimates are published as volumes of the NOAA Atlas 14, Precipitation-Frequency Atlas of the United States, and are available online on the NOAA (2017) Precipitation Frequency Data Server.

Methods for computing the NOAA Atlas 14 precipitation estimates evolved in regard to regionalization of the information, from one based on L-moments (Hosking and Wallis 2009) to one based on a region-of-influence approach (Burn 1990), but at-site statistics were based on L-moment statistics calculated from annual maximum time series in all volumes of Atlas 14. The precipitation frequency estimates in NOAA Atlas 14 supersede the estimates published by NWS between the 1950s and the 1980s, and are greatly improved in terms of accuracy, reliability, and spatial resolution. The updated estimates contained within NOAA Atlas 14 benefit from:

- Denser precipitation gauge networks with longer periods of record and extensively quality-controlled data.
- Use of regional frequency analysis methods that allow for the development of rare frequency estimates, a wider range of frequencies and durations, and uncertainty around those estimates.
- Numerous internal consistency checks across frequencies and durations in the production of (IDF) curves.
- Use of the latest techniques for spatial interpolation and mapping that take into account variations in terrain.
- Estimates are provided at high spatial resolution (~800 m) grids.
- Estimates accessible to the public through a web-based interface.

NOAA Atlas 14 development funding comes from external sources via cost reimbursements made possible by memoranda of understanding between NOAA and several Federal, State and local supporting partners. The cost-reimbursement funding approach dictates that updates are done in volumes based on State boundaries, and produced in a serial, non-parallel workflow stretching over many years. For example, since early 2000, NOAA has developed 11 Atlas 14 volumes.

Volume 11, covering Texas, was published in 2018 and is the latest complete volume in the series. Currently, the HDSC group is working on developing and updating estimates for Idaho, Montana, and Wyoming as Volume 12 that, once complete, will supersede estimates (for 1-hour to 24-hour duration) from the 1973 Precipitation Frequency Atlas of the Western United States.

NOAA's precipitation frequency estimates are used for a wide variety of design and planning activities at the Federal, State, and local levels, including the private sector. Precipitation frequency estimates are used to design culverts, bridges, and parking lots, as well as sewer and stormwater infrastructure. Water resources engineers use them to estimate the amount of runoff, the volume of detention basins, and the size of their outlet structures. Furthermore, floodplain managers also use precipitation frequency estimates as inputs for hydrologic and hydraulic models used to delineate floodplains and regulate the development within floodplains, which is crucial for all communities participating in the NFIP.

NOAA has also begun working on adjusting IDF analysis to reflect observed and projected changes in climate. In order to understand the potential impact of nonstationary climate conditions on precipitation frequency estimates, in 2016, the Federal Highway Administration (FHWA) tasked NOAA’s HDSC with examining this issue in collaboration with academic partners. This collaborative effort aimed to develop a method that would investigate and allow for nonstationary climate effects to be integrated into the NOAA Atlas process, make use of future conditions from climate models, and understand the limitations and applicability of different techniques for developing future nonstationary precipitation frequency estimates. The report "Analysis of Impact of Nonstationary Climate on NOAA Atlas 14 Estimates", was completed in June of 2020 in collaboration with Pennsylvania State University, the University of Illinois at Urbana-Champaign and the University of Wisconsin-Madison (NWS 2022).

Groups outside of NWS have undertaken efforts to develop climate-informed IDF curves. One widely used tool is the FHWA web-based tool for computing CMIP precipitation time series into useful metrics for transportation planning (FHWA 2020). The tool permits analysts to identify locations and planned project beginning and ending dates and access, download, and post-process CMIP output for up to 32 different GCM models stored on a USBR website. The resulting model data extraction is stored in a netCDF file. A follow-on processing service examines the information and compares the daily rainfall totals for past extreme events simulated by user-selected GCMs to observed data to develop daily ratios. The ratios are used to adjust existing Atlas 14 IDF data for expected future conditions anticipated for the project planning period.

NOAA and the Department of Defense’s Strategic Environmental Research and Development Program (SERDP) through the North Carolina Institute for Climate Studies conducted a similar effort that resulted in the creation of additional climate-change impacted IDF curves (North Carolina Institute for Climate Studies and NOAA n.d.). Two GHG emissions scenarios are provided: RCP8.5, which is a high-emissions scenario with large GHG increases through the 21st century; and RCP4.5, which is a mid-range GHG emissions scenario where emissions increase through 2050 then stabilize. These estimates were derived using NOAA Atlas 14 values as the initial estimate and then adjusting them (Kunkel et al. 2020).

#### *Other Environmental Conditions*

The 2015 CISA Appendix also acknowledges the effects of non-climatic changes in watershed conditions, including reservoirs, land use change, channel change, burned areas, and VLM, on flood hazards. However, no specific methods for adjusting future flood hazards for these effects were recommended despite a long history of Federal legislation and guidance that considers these impacts. The 2015 Appendix notes that, "in 1956, the U.S. Bureau of Public Roads (Bureau of Public Roads 1954) developed standards for the yet-unbuilt Interstate Highway System that required the hydraulic design of bridges and culverts to consider future land use occurring 20 years after construction." The Clean Water Act (§204 and §208) also considers "projected population and associated commercial and industrial establishments" (albeit for sanitary, combined, and urban storm runoff).

Data-driven and process-based models of current and future flood hazards considering the flood impacts of changes in land use and other non-climatic environmental drivers have proliferated since 2015. Many statistical nonstationary flood frequency models relate changes in various indicators of watershed conditions, including indicators of urbanization (e.g., Over et al. 2016; Debbage and Shepherd 2018; Blum et al. 2020; Hecht and Vogel 2020), wildfires (e.g., Wagenbrenner et al. 2021), and reservoir indicators (e.g., Xiong et al. 2020). Many process-based modeling studies have also evaluated the implications of changes in watershed conditions on extreme floods, including land use (e.g., Yu et al. 2019) and wildfires (e.g., Rengers et al. 2016). Both statistical (Xiong et al. 2020) and process-based studies have also examined concurrent changes in climate and watershed conditions and, in some cases, have attempted to partition observed changes into climatic and non-climatic components (e.g., Woltemade et al. 2020; Yang et al. 2021). The effects of channel changes on peak flow magnitudes have not been considered as extensively as changes to basin characteristics in data-driven analyses despite their contribution to changes in flood hazards (Slater et al. 2015).

### *Element 3: Streamflow (Hydrology)*

Since 2015, many methodological advances have been made for adjusting design floods so that they reflect current and future climate and watershed conditions. Data-driven methods for adjusting estimates of large floods for infrastructure design (design floods) at gauged sites have proliferated (see reviews by Villarini et al. 2018; Salas et al. 2018; François et al. 2019; Slater et al. 2021; Wasko et al. 2021; Nerantzaki and Papalexiou 2022; Mishra et al. 2022), including newer artificial intelligence methods, such as deep learning (see review by Bentivoglio et al. 2022). Many studies have also simulated the flood impacts of projected climate changes using process-based hydrological models (e.g., Maurer et al. 2018; Dullo et al. 2021). However, there have been few comparisons of data-driven and process-based modeling approaches for projecting extreme floods in the United States and elsewhere (Schlef et al. 2021). Moreover, in a split-sample validation analysis of observed peak flows at gauged sites in the conterminous United States, Schlef et al. (2021) found that statistical "precipitation-informed" models using GCM hindcast values of precipitation produced more accurate and precise estimates of regional trends than process-based hydrologic simulation models. In contrast, process-based hydrologic simulation models were more likely to yield better estimates of the direction of change in peak flows with a 1-percent annual chance in minimally disturbed basins. In many regions, modeled estimates of floods with a 1-percent annual chance exhibited a strong negative bias during the historical period. This might arise from a model smoothing effect that stems from the omission of calibration residuals in simulated responses, a common practice that attenuates estimates of extremes from continuous simulation models (Farmer and Vogel 2016). Meanwhile, Schlef et al. (2021) also acknowledge that there are opportunities to improve upon the "precipitation-informed" projections that they evaluated by also considering (i) changes in temperature and (ii) larger-scale atmospheric-oceanic patterns, which GCMs often simulate more accurately than localized precipitation. In fact, Schlef et al. (2018) demonstrate this possibility using sea-surface temperatures and geopotential height outputs from an ensemble of GCMs as predictors of flooding. This suggests that data-driven projections of climate-induced changes to peak flows should also evaluate associations between underlying atmospheric conditions and not just meteorological variables with more proximal effects on peak flows, such as precipitation.

Ongoing comparisons of data-driven and process-based approaches to future flood projection are needed to support CISA implementation as they continue to evolve. To isolate climate sensitivities from other drivers of hydrologic change, more benchmarking comparisons in minimally disturbed basins must be conducted. However, these comparisons must also be extended to basins where water resources management interventions, such as reservoirs and diversions, and other anthropogenic perturbations, such as land use change, substantially impact streamflow. Profound changes to aspects of river corridor landscapes, such as topography, vegetation, and soil, can also affect streamflow routing. These impacts should also be considered in river corridors that have recently experienced rapid changes of this nature.

In addition to the lack of consensus regarding the selection of methods for making future flood projections, climate-informed science approaches to project design in other countries often use national or regional percent-change “safety factors” informed by climate studies instead of basin-specific projections coupling climate scenarios with hydrologic and hydraulic models (Wasko et al. 2021). Many of these safety factors are only applied to peak precipitation intensity. Wasko et al. (2021) observe that only El Salvador, Norway, and some jurisdictions in the United Kingdom explicitly consider climatically driven changes in riverine flood peaks in their guidance. El Salvador recommends a safety factor of 30–40 percent for bridge design plus criticality-dependent freeboard (Dirección de Adaptación al Cambio Climático y Gestión Estratégica del Riesgo 2014). Norway has employed regionally varying percent-change safety factors ranging from 0–40 percent (Lawrence and Hisdal 2011; Scottish Environment Protection Agency 2019). Only England and Wales have developed basin-specific projections directly from downscaled GCM data (UK Government Environment Agency 2016; Natural Resources Wales 2021). These change factors also recognize the planning horizon of a project (Griffin et al. 2022). The CISA can accommodate these different approaches to design flood adjustment if they reflect the best-available science at the time.

In addition to climate-driven projections, scientific advances since 2015 could enhance FFRMS implementation using other floodplain definitions besides the CISA approach. Notably, the publication of Bulletin 17C (England et al. 2019) provides updated guidance for estimating the 1-percent- and the 0.2-percent-annual-chance floods at or near gauged sites. Moreover, the Expected Moments Algorithm it recommends can incorporate imprecise paleoclimate and historical flood data, which enables evidence of large floods outside of the instrumental record to be considered in design flood estimates, and perception thresholds, which introduce knowledge where data gaps might otherwise exist. The USGS (2016b) StreamStats tool has also extended Bulletin 17C estimates of the 0.2-percent- and 1-percent-annual-chance peak flows to ungauged locations in many parts of the United States (e.g., Wagner et al. 2016; Zarriello 2017). The guidelines in this bulletin are applicable for estimating the 1-percent- and 0.2-percent-annual-chance peak flows at gauged sites.

### *Element 3a: River Corridor Landscape Change (Including Erosion)*

Fluvial erosion hazard (FEH) mapping delineates areas adjacent to the channel that may be impacted by channel change (channel downcutting, aggradation, and lateral migration). Following previous determinations by FEMA (1999), there has been much scientific advancement in mapping hazard zones related to geomorphic change since 2015 (e.g., Burke Engineering 2018). Because of the spatial and temporal complexity in geomorphic processes that result in river channel change, FEH mapping requires many sources of data, including historical channel change, geomorphic and engineering analysis, mathematical modeling, numerical modeling, and GIS techniques. The 2015 CISA Appendix noted that no one technique was adequate to address site-specific conditions that represent a range of possible geomorphic processes.

Zones of expected river-channel changes are located where flood flows can change the channel geometry as well as the surrounding landscape. The geologic and geomorphic setting drives the steepness of the channels, which then powers the erosivity of streamflow while underlying bedrock, soils, and channel bedforms resist those erosive forces, ultimately reaching a dynamic equilibrium for that setting (MacBroom et al. 2017; Lane 1955). These interactions of erosion and resistance change the flux of sediment to downstream reaches, which can cause additional geomorphic change (Gartner et al. 2015).

Hazardous geomorphic processes can be grouped into three major categories: (i) degradation or downcutting and channel bed erosion, (ii) lateral migration and bank erosion, and (iii) aggradation or channel bed deposition and braiding/bar formation. In headwaters, degradation might be located where ephemeral (dry except for during runoff events) channels with confined valleys can erode their beds and vertically downcut stream channels. The downcut channel propagates adjacent hillslope failures and debris flows. It also initiates headward progression of gullies that may extend into upland flats, such as in first order tributaries that intersect steep valley sides of large rivers. In perennial meandering main stem channels with floodplains, lateral migration may be accelerated by increases in peak flows and sediment load, causing channel widening and bank erosion into infrastructure. Aggradation and deposition may happen in channels that transition from steep slopes to flat slopes and have an abundant upstream sediment supply. Aggradation and bank erosion can happen where overbank flows are constricted, often by infrastructure, raising the streamflow's erosive power to levels that cross a geomorphic threshold that separates more narrow meandering channels from wider braided channel types. For erosion to occur, the forces of the water (amount of streamflow multiplied by channel slope) need to overcome the resisting forces of the materials that make up the bed and banks (consolidation of rock type, cohesiveness or size of bank and bed sediment).

Peak flow unit stream power has been identified as a useful metric for quantifying thresholds for geomorphic adjustments in some situations (Yochum et al. 2017). Spatially-varying shallow groundwater contributions from intense rainfalls can also trigger near-channel landslides in addition to runoff hydraulic forces (Jennings et al. 2016).

Multiple agencies began mapping advisory-level river channel change hazard zones in the mid-2000s (Kline and Cahoon 2010; Burke Engineering 2018). At the core of each of these approaches is mapping a river corridor where the river has meandered or changed course in the past and has the potential to do so in the future (see Box D for an example). This corridor is similar to the active river area described by the Association of State Floodplain Managers (ASFPM) and The Nature

Conservancy (2008) and the geomorphically-defined meander belt zone, and differs from floodways and FEMA-designated 1-percent-annual-chance floodplains (Kline and Cahoon 2010).

The GIS-based approaches for mapping river corridors susceptible to channel change use a combination of methods at a variety of scales and resolutions. Approaches include estimation of a common meander belt width based on bankfull channel width, digital topology-based delineation of valley bottoms, floodplain maps, aerial photograph identification of valley bottomland and abandoned channels, and field-based geomorphic assessments of actively migrating and relatively stationary reaches (Gartner et al. 2019). Uses include identification of vulnerability and risk of damage to property and infrastructure, identifying risks to stream crossing infrastructure, flood hazard planning and mitigation, and adoption of active and passive management strategies that help reduce future risk, including natural flood management techniques (Gartner et al. 2019). Future streamflow conditions from climate change have not been included in these agency approaches, but they could be if changes in flow characteristics were to be linked to how they might affect erosion potential or expand meander belt and FEH corridor widths. Agencies are encouraged to consider adopting these existing approaches for identifying zones of channel change and other geomorphic hazards when the geomorphic setting, project criticality, and agency expertise are well suited for it. Under these circumstances, agencies are encouraged to produce floodplain maps that feature FEH zones, along with floodplain inundation information.

On a different spatiotemporal level is an interaction between geomorphic change and how it affects flood inundation regardless of other direct erosion or deposition induced hazard zones (Slater et

*Box D. Delineating Channel Change Hazard Corridors in Indiana*

Mapping approaches for delineating channel change corridors are done at the river reach scale and involve data collection from the field, historical aerial photographs, and geomorphic data gathered from computerized geospatial analyses tools and applications of stream network characteristics based on overlaid digital elevation models of landscape topography. Many approaches for streams with drainage areas larger than 1 $km^2$ start with an initial calculation of the bankfull channel width, which is done in the field or with regional or State-based hydraulic geometry equations based on drainage basin area. Next, the lateral mobility is determined for the reaches, based on aerial photograph analyses or field-based geomorphic assessments of “stationary” or “actively migrating” (Robinson 2013). The lateral mobility is then considered when computing the corridor width as a multiplier of the bankfull width. These corridors can be mapped using stream centerlines available from the USGS (1997) National Hydrography dataset as a point of reference. In Indiana, for example, geomorphically stationary streams had a corridor width of one bankfull channel width or 100 feet, whichever was greater (Meunier et al. 2018). In contrast, for actively migrating channels in Indiana, the corridor width was estimated to be 8 times the bankfull channel width. The corridor widths are manually checked and verified. Fluvial erosion hazard corridors for streams in Indiana can be viewed on an Indiana Department of Natural Resources webmap (Indiana Silver Jackets Hazard Mitigation Task Force 2016). Additional background information on fluvial erosion hazards is available from USGS (Leroy et al. 2020).

al. 2015). If a channel degrades, flood flows may not inundate a floodplain as readily, lowering flood depth. However, the more chute-like channels are likely prone to bank erosion. Contrarily, if a channel aggrades, flood depths may increase even when the size of the peak flood remains unchanged. Furthermore, additional insights on which channels are susceptible to geomorphic change could be gained by not only looking at peak flows and related energy expenditure but also flood durations relative to erosion thresholds (Costa and O'Connor 1995).

### Element 3b: Water Resource Management Impacts

The 2015 CISA Appendix does not describe any specific approaches for adjusting current and future design peak flows and their resulting water levels for the effects of water resource management, including reservoirs, diversions, or flood barriers, despite their well-established impacts on streamflow and inundation. Studies on the effects of these management interventions on streamflow and inundation have continued to proliferate (e.g., Wang et al. 2017b; Blöschl 2022; Xiong et al. 2020). Analysts should choose methods that account for the unique water management practices employed in the watershed of interest.

### Element 4: Streamflow, Land, and Channel Interactions

Hydraulic modeling has undergone extensive advancement in recent years that has resulted in simpler and better guided user experiences. Multidimensional models (USGS 2008) are now routinely applied to increasingly available LiDAR-based topobathy data. Multidimensional models have the distinct advantages that they can be applied to more complex channels where simplified 1D models cannot be applied without degrading modeling results and where many formerly limiting computational assumptions can be relaxed. These models are often accompanied by geospatial tools and functions that permit rapid development of high-resolution computational grids. The USACE Hydrologic Engineering Center's River Analysis System (HEC-RAS; USACE 2020), for example, allows the user to perform 1D steady flow, 1D and 2D unsteady flow calculations, as well as sediment transport/mobile bed computations. The International River Interface Cooperative software (iRIC) performs numerical simulation of flow and channel morphodynamics of river channels. iRIC includes the functionality of the Multi-Dimensional Surface-Water Modeling System, developed by the USGS and RIC-Nays (developed by the Foundation of Hokkaido River Disaster Prevention Research Center) (USGS 2019). These applications facilitate the development of flood-inundation and channel erosion maps. Documentation and online training are available on iRIC’s website (Shimizu and Nelson 2007)

### Element 5: Data Sharing and Visualization of Riverine Hazard Information

Large flood events, flood insurance reforms, and anticipated increases in flooding due to climate change have all prompted widespread attention to the communication of riverine hazards in recent years. From the 1970s to 2021, flood insurance rates were predominantly based on relatively static measurements, emphasizing a property’s elevation within the Special Flood Hazard Area on a FIRM. FEMA is updating the NFIP’s risk rating methodology through the implementation of a new pricing methodology, Risk Rating 2.0. With Risk Rating 2.0, FEMA now has the capability and tools to address rating disparities by incorporating more flood risk variables. These include flood frequency, multiple flood types—river overflow, storm surge, coastal erosion, and heavy rainfall—and distance to a water source along with property characteristics such as elevation and the cost to rebuild. Concurrently, FEMA is exploring improving the understanding of flood hazard and risk through the FFRD initiative. This initiative follows recommendations from the TMAC

(2022) and has also recommended the inclusion of uncertainty on floodplain maps and other data products.

Recent research has also addressed the challenge of communicating flood risk in settings where it is changing over time—whether due to climatic factors or changes in other environmental conditions. Probabilistic methods have been developed for expressing the reliability of a project over a planning horizon for a single scenario of flood hazard change (Read and Vogel 2015; Yan et al. 2017; Jiang et al. 2019). Multi-scenario evaluation methods have also continued to be advanced, including for cases in which future flood scenarios are too uncertain to be assigned probabilities reliably.

While the 2015 CISA Appendix emphasized the importance of making decisions robust to plausible future climate conditions, specific guidelines for evaluating the robustness of these decisions were not prescribed. One challenge to the widespread implementation of multi-scenario methods for project evaluation is that decision metrics often reflect the risk tolerance of the decision maker(s). Comparative studies, such as McPhail et al. 2018, can serve as a starting point for efforts to develop guidelines that help agencies select multi-scenario decision metrics appropriate for their needs.

Finally, recent efforts at the State and local level have been made to identify and communicate geomorphic hazards in addition to inundation hazards (ASFPM Riverine Erosion Hazards Working Group 2016). Some of these efforts are described further in Section IV. B.

### *Model Integration Considerations*

Modeling the effects of climate change on riverine hazards requires an understanding of how climatic and other environmental changes affect streamflow, hydraulics, and fluvial geomorphology. To date, there are relatively few examples of coupled multi-model workflows that examine floodplain inundation resulting from future climate projections (Alfieri et al. 2016; Wing et al. 2018; Dullo et al. 2021; Callaghan and Hughes 2022; see Box E) despite countless studies that (i) simulate hydrologic impacts of climate change and (ii) examine floodplain depths resulting from a given set of hydrologic conditions. Increasingly, such analyses are being developed and published for public use, such as the parcel-scale inundation projections under future climate scenarios for the conterminous U.S. (CONUS) carried out by the First Street Foundation (n.d.). Expensive computational requirements are one major constraint to implementing these modeling chains. Challenges in simulating future climate extremes and their propagation to streamflow and inundation extremes require models with fine spatial and temporal resolutions, which exacerbate these computational demands. Coupling hydrologic changes with geomorphic ones augments these computational demands even further. While such couplings of process-based models should continue to be pursued, less computationally intensive approaches should also be evaluated. For example, the application of "climate-informed" models that relate GCM-derived climate variables with inundation levels through data-driven techniques may be useful for predicting future changes in inundation.

In any case, a coherent strategy is needed for deploying and assessing model chains that examine the effects of climate change on riverine hazards. In addition to evaluating different models that use various techniques of varying degrees of computational complexity, it is important to establish practices that allow for the effects of cascading errors and uncertainty—arising from data, models, and future conditions—to be quantified. In addition, potential incongruences in the spatial and temporal scales at which processes are being simulated must be assessed. The need for agencies to select model chains in line with their skill sets and budgets also motivates the consideration of multiple approaches for integrating these elements of the workflow. Indeed, one pivotal consideration will be the extent to which the flood inundation under future climate and land use conditions can be pre-computed for agency users given the training and computational capacity needed to produce these simulations efficiently.

### Box E. *Assessing Climate-Change-Induced Flood Risk Using GCM Outputs*

The analytical workflow described in Figure 7 does not prescribe a specific approach to the simulation of climate impacts on future flooding. Depending on available data, agency and analysts' preferences, and project requirements, different approaches are possible. For instance, many analysts may choose to employ statistically-based modeling of flood trends and patterns where the data are available. Others may choose to use a design-storm construct expressed through climate-change impacted rainfall IDF curves that may be obtained now from the FHWA CMIP Climate Data Processing Tool or DOD/NCICS websites and applied through readily available rainfall-runoff models.

But there are weaknesses to this approach. The implied underlying hydraulic assumption is a steady flow regime: (1) looking at the peak flow produced by the design storm and (2) typically assuming that the peak flow represents the most critical operating hydraulics allows the designer to consider "critical" hydrologic conditions for some associated probability. In reality, however, a flood event is actually a hydrograph, whose shape is not only a function of the precipitation but also its interactions with the channel, floodplain, and infrastructure. The cumulative exposure of the structure to the full duration of the hydrograph associated with the peak flow may represent the true critical design condition that only continuous modeling approaches provide. This makes approaches that examine inundation over the course of an entire flood event (the full hydrograph) especially prudent. Capturing the impacts for sustained, long-duration hydrographs may require selection of storm durations longer than the minimum duration required for time of concentration considerations and for flow contributions from the furthest points in the basin to reach the outlet. Although considered out of scope for this SotS review, the selection of storm and flood duration for flood simulations deserves increased scrutiny and research given its importance when implementing the FFRMS.

*[Box E continues on the next page.]*

Box E. *Assessing climate-change-induced flood risk using GCM Outputs (continued)*

In addition, process-based hydrologic-hydraulic modeling that simulates inundation over the course of entire flood events using projections of future climate conditions based on specific GHG pathways is also possible, as exemplified by Dullo et al. (2021). First, the authors modeled streamflow at 3-hour intervals over periods of several decades. Then, they extracted flood events generated by their hydrologic model to produce a time series of flood areas and depths using their hydraulic model. Next, they analyzed those time series to develop probability distributions of flood depth at each pixel within their study area. The process is probably more involved than typical agency projects/actions may warrant, but their unique approach has some significant advantages over the statistically based modeling or design-storm approach. In addition to examining flood inundation during entire flood events, this approach permits modelers to retain control over the selection of specific GHG pathways. Moreover, it enables modelers to examine more diverse scenarios in detail, looking, for example, at potential climate impacts on flood antecedent conditions, soil-infiltration behaviors, evapotranspiration rates, and other climate-hydrology interactions that are potentially even more uncertain than future rainfall conditions. Evaluation of such considerations may be warranted for major projects expected to produce critical benefits.

## C. Roadmap: Needs and Opportunities to Improve Projections

A principal consideration for the CISA option is the “actionability” of climate simulation and engineering analysis tools. If tools and data are not readily available, agencies will not be able to implement the CISA option and will have to default to the use of the FVA or 0.2PFA options, potentially resulting in projects that may be either under-designed (and thus still vulnerable) or over-designed (constructed at higher than necessary cost) against flooding. The development of the Riverine Flooding Workflow (Figure 7) in combination with the review of the state-of-the-science advancements since 2015 (Section IV. B. Advances in Understanding and Actionable Science) provide an opportunity to identify scientific and methodological gaps complicating or preventing CISA implementation.

### *Short-Term Roadmap Elements*

Many riverine workflow process improvements are already nearing completion or merely require promotion and adoption. These improvements are considered “short-term roadmap elements” and are described below.

**Project framing:** Provide initial guidance on selection of appropriate climate change scenarios, return periods, and time frames

**Stationary precipitation IDF curves:** IDF curves are the common basis for hydrologic simulation where streamflow data are unavailable. For over a decade, NOAA has been developing regional IDF computations published as 11 component volumes of Atlas 14 and as a web-based tool (NWS n.d.). NOAA is currently working on developing the precipitation frequency estimates for Idaho, Montana, and Wyoming as Volume 12. Compilations for Washington and Oregon remain unavailable. This design-storm approach is best suited for small or flashy watersheds where antecedent storage conditions have little impact on storm runoff. These IDF curves represent substantial improvements over earlier design storm estimates and utilize recent precipitation data but do not consider trends in precipitation over time.

**Flood frequency analysis:** Agencies should adopt Bulletin 17C (B17C) for estimating the 1-percent- and 0.2-percent-annual-chance peak flows (essential for non-CISA options) for locations at or near applicable stream gauges. The USGS StreamStats tool uses regional regression equations to extend estimates to many ungauged locations. StreamStats currently has peak-flow regression equations in StreamStats for 44 states and regions. Additional studies are underway. A systematic update for the remaining States is needed.

**Hydraulic modeling:** Agencies are encouraged to use multi-dimensional hydraulic models where high-resolution geospatial datasets are available and hydraulic conditions merit. As described in Section IV. A. Riverine Workflow, multiple dimensional models are widely available. Available agency models include the USACE HEC-RAS (2020) and USGS iRIC (USGS 2019). In many instances, these 2-D models may be more cost-effective to use than simpler, less informative 1D models. Models are also available for simulating hydrodynamics in channels underlain by mobile beds and banks. New onsite and virtual training approaches may be needed to facilitate the adoption of these models.

**Data sharing and visualization:** Prototypes for communicating both inundation and channel change risk are needed. Some U.S. States, such as Vermont, have developed versions of flood hazard maps that include both inundation information (as is commonly presented in FEMA FIRMS) and channel change hazards.

### *Medium-Term Roadmap Elements*

**Service life impacts:** Evaluate reliability for projects of different service lives using probabilistic techniques that account for changing flood hazards (Read and Vogel 2015; Yan et al. 2017; Jiang et al. 2019).

**Multi-scenario analysis guidelines:** Guidelines for multi-scenario project analysis are needed. Scenario analysis is an essential tool for the CISA option, yet there are no Federal guidelines for conducting such analyses. In addition, downscaling global climate model results and mapping those against basin boundaries can be a time-consuming activity requiring skilled data scientists. Agencies would benefit from access to tools that standardize, expedite, and automate that work.

**Non-climatic scenarios:** Identify land use/cover/management scenarios, including land-cover disturbances such as wildfire, for use in future-flood projections.

**Flood scenarios:** Evaluate methods for developing riverine flooding scenarios.

**Atlas 15 projections:** Develop new hydrometeorological atlases to incorporate GCM-simulated IDF data. Ensure that nonstationary methods capture and extend precipitation trends based on the latest precipitation gauge observations and incorporate projected future precipitation from climate models.

**Climate change impacted IDFs:** The current NOAA Atlas 14 approach assumes stationarity in the extreme precipitation time series data and methodology used for frequency distribution selection and fitting. Based on the key findings from the study by NOAA HDSC and academic partners (NWS 2022), NOAA is considering replacing the current Atlas 14 regional L-moment statistics with a nonstationary regional Generalized Maximum Likelihood approach in the first volume of the upcoming Atlas 15. This nonstationary regional maximum likelihood approach calculates precipitation frequency estimates at grid locations by pooling information from nearby gauge locations or gridded precipitation products and weighting the extreme events using a kernel function and a bandwidth. The proposed methodology eliminates the need for trend detection and instead adapts to trends in data when they exist (positive or negative) or give a nearly stationary fit when a trend does not exist. The trend in data can be informed by incorporating independent variables called covariates—such as radiative forcing, annual temperature, or time—into the calculation of the distribution parameters.

Four World Climate Research Program's Phase 5 (CMIP5) downscaled climate datasets were evaluated in the HDSC study: Statistical Localized Constructed Analogues, LOCA; North American Coordinated Regional Downscaling Experiment, NA-CORDEX; Bias-Correction and Constructed Analogs, BCCAv2; and University of Wisconsin Madison Probabilistic Downscaling, UWPD. The results showed that the variability of future projections among the retained datasets should be regarded as significant. The datasets' variability results in a high level of uncertainty regarding future projected changes and, as such, needs to be considered when applied to engineering design. Given that none of the downscaled climate models outperformed the others in this study, the use of a multi-model approach may better characterize the uncertainty associated with climate model predictions for the precipitation frequency estimates. Moreover, the analysis revealed that, as other studies have found, climate models could be a good tool to account for the change in future climate, but using model-based precipitation frequency estimates directly may not be adequate for engineering design because the synthetic data may not have covered the required precipitation depth or storm-duration adequately or with sufficient resolution. Instead, downscaled datasets could be applied as a relative change between the present and future precipitation frequency estimates (quantile delta change method) that can be used to extend the estimates developed based on past observations into the future. The use of climate model information for hourly durations and higher annual recurrence intervals requires further investigation.

**Mixed population analysis:** "Bulletin 17C-style" consensus guidance for analysis of "mixed populations" in flood records is needed. Although most flood-frequency models, including the one in Bulletin 17C, assume that flood data arise from a single population, many flood records are composites containing floods produced by distinctively different storm types or hydrologic conditions. Prior research has demonstrated the importance of accounting for the statistical properties of each flood type separately before combining them into a composite distribution for flood-frequency analysis (e.g., Morris 1982; Hirschboeck 1987; Barth et al. 2019; Yu et al. 2022). Despite the established benefits of mixed-population analyses, current databases do not support the special handling that they require. In particular, they often do not contain information about causal mechanisms of observed flood events. For example, the annual peak-flow files used in the National Water Information System generally do not indicate any information about the meteorological drivers of events (e.g., tropical cyclone, atmospheric rivers, convective storms) or antecedent conditions preceding them (e.g., snowpack, soil moisture storage). Due to climate change, there is a growing need to advance models and establish consistent procedures for such studies, especially ones that account for changes in the proportion of events arising from different causal mechanisms over time (Huang et al. 2022). In addition, approaches that address the contributions of different mechanisms to individual flood events, such as copulas, merit further research. FEMA, USACE, and USGS are currently conducting a joint project to improve methods for addressing mixed populations. USACE has already incorporated mixed-population analysis into its HEC-SSP software to speed up implementation (USACE n.d.).

**Flood statistics:** Interagency developmental efforts are needed to systematically and proactively estimate and disseminate future conditions peak-flow statistics for gauged and ungauged locations throughout the Nation for subsequent use by agencies performing CISA analysis. Such efforts could be based on high-resolution topographic data, incorporate water and flood management practices and infrastructure, and result in a readily available catalog of consistent flood statistics. Maintaining these statistics would require frequent updates as improved models and methods become available.

**Channel change hazard mapping:** Regional FEH mapping techniques used in Vermont, Indiana, New England States, and Washington could be applied nationally. These State-based methods likely have potential application on regional and national scales and could form the foundational framework for more routine identification and communication of fluvial erosion hazards. Less commonly available are watershed-scale GIS approaches for addressing flood-related geomorphic changes in headwater ephemeral channels, such as mass wasting and landslides, and compounding geomorphic hazards in downstream reaches (for example, a change in channel location [avulsion and meander cutoffs] and channel planform changes from meandering to braided [as occurs in New England's river process corridor; Gartner et al. 2019]). Currently the nationally available 10-meter 1/3 arc-second digital elevation models have been successfully used to estimate near-channel landslides (Gartner et al. 2019). Under discussion are questions of how the zones need to be widened due to increases in the size of floods that an area might expect due to climate change or other environmental changes, although studies using a sensitivity analyses approach in Quebec had positive results for zones remaining valid under future climate scenarios (Buffin-Bélanger et al. 2015). Of additional importance are digital maps of alluvium, surficial and buried unconsolidated sediment, and bedrock found in soils and geologic maps applied to a river corridor zone. These maps help to estimate the erodibility of the land near the channel from both perspectives of hydraulic resistance and storm-related groundwater-related through-flow (MacBroom et al. 2017; Jennings et al. 2016; Sholtes et al. 2018).

**Automation of channel change hazard mapping:** Consider automation of methods for reach-scale mapping of all potential types of flood-caused channel changes that include degradation, channel widening, and aggradation (i.e., potential USGS StreamStats application).

**Flood inundation maps for Federally-owned lands:** Consider a pilot project to map flood-inundation of Federally-owned lands using the NWS National Water Model (NWM) and CONUS 404 simulations. The NWM has national scope and a 4-km spatial and hourly temporal resolution, and existing 40-year retrospective simulations of historic flooding could be used to estimate the 1-percent- and 0.2-percent-annual chance for CONUS streams at the National Hydrography Dataset resolution. Both the NWS and USGS have plans for simulating 40-year future flood realizations using future climate scenarios. Such an effort is consistent with the 2022 Consolidated Appropriations Act language concerning future NOAA hydroclimatology studies.[14] Though FEMA does not map floodplains for most federally owned lands, this proposed pilot effort could provide developmental support for FEMA's FFRD initiative and result in timely products for

[14] *See Consolidated* Appropriations Act. 2022. H. Comm. Prt. pp. 232-233 (March 9, 2022). https://www.congress.gov/117/cprt/HPRT47047/CPRT-117HPRT47047.pdf

FFRMS implementation on lands that will otherwise lack FEMA data. These lands account for approximately 1/3 of CONUS stream miles.

### *Long-Term Roadmap Elements*

**Coherent climate and land use scenarios:** Designate a set of coherent climate and land use change scenarios. The development of future flood conditions maps and products has been greatly facilitated by the adoption of consensus sea level rise projection scenarios. The riverine community has no equivalent. The generation of climate-hydrologic scenarios would be consistent with congressional instructions to NOAA included in the 2022 Consolidated Appropriations Act concerning creation of basin-scale hydrometeorological projections.[15] While land use and zoning are local prerogatives, national and regional-scale projections of future land use are possible and could form the basis for simulation of non-climate drivers needed for CISA analyses. In addition, these scenarios could help inform local land-use decisions.

**Adopt nonstationary flood frequency analysis guidelines:** Develop and adopt "Bulletin 17C consensus style" guidance for nonstationary flood frequency analysis, including the adjustment of design events to reflect current and future conditions. This includes adjustments that account for phenomena that drive gradual trends (e.g., urbanization), abrupt changes (e.g., reservoir construction or re-operation), episodic events (e.g., wildfires) and multidecadal climatic persistence (e.g., climate oscillations). Numerous recent studies that evaluate methods for incorporating nonstationary into estimates of design events under current and future conditions (e.g., Strupczewski et al. 2001; Read and Vogel 2015; Yan et al. 2017; François et al. 2019; USACE 2020; Schlef et al. 2021; Sharma et al. 2021; Wasko et al. 2021; Coelho et al. 2022; Hecht et al. 2022; Vidrio-Sahagún and He 2022) could provide a useful basis for consensus Federal guidelines addressing future flood projections. GCM-derived covariates that demonstrate strong relationships with floods during historical periods could be prime candidates for modeling adjustments for future conditions. In some cases, underlying atmospheric variables that drive flood-inducing weather patterns may serve as better predictors of floods than extreme precipitation values (Schlef et al. 2018).

**Topobathy data:** Improve the availability of high-resolution LiDAR and channel topobathy data. The USGS National Geospatial Program is developing and deploying methods for using LiDAR technology for simultaneously collecting both topographic and bathymetry (subsurface channel topography) data. These data plus data produced by more transitional sweeping fathometer instruments operated by agencies such as the USACE are resulting in increased opportunities for applying multi-dimensional models to floodplain mapping in the future.

**Channel change science:** Improve our understanding of how land use and climate drivers cause channel change to better inform riverine hazard management and mitigation strategies. Specifically: (i) How do changes in flood characteristics (including frequency and duration) affect flood energy and related erosion potential and bankfull dimensions?; (ii) How can high-resolution hydrography be used to further define headwater channels prone to erosion?; and (iii) How can agencies incorporate multi-year remotely-sensed digital elevation models, such as those from repeat aerial LiDAR surveys, to document and quantify zones of channel change, including headwater degradation, lateral migration, and aggradation?

[15] *See* Consolidated Appropriations Act. 2022. H. Comm. Prt. pp. 232-233 (March 9, 2022). https://www.congress.gov/117/cprt/HPRT47047/CPRT-117HPRT47047.pdf

**FFRD:** Develop new FEMA flood-risk mapping products and datasets using probabilistic modeling techniques. FEMA's FFRD initiative holds enormous potential for accelerating the development of floodplain maps and data describing future conditions. FFRD and its application to mapping future flood conditions have been reviewed and endorsed by the TMAC.

## V. Assessing Future Pluvial Flooding

The word "pluvia" is Latin for "rain." The word "pluvial" referred to cloaks worn by European clerics around the 17th century to protect themselves from that rain.[16] Planners and scientists adopted the term to denote flooding from rainfall events. Therefore, pluvial flooding refers to that component of flooding that is a result of rainfall.

More precisely, pluvial flooding is the hydrologic collection of water at a land location not otherwise within associated fluvial (i.e., riverine) or coastal floodplains or having direct drainage to these floodplains. Within this context, these locations are not considered FFRMS coastal or fluvial floodplains. However, they may have an indirect nexus to those (and other) types of floodplains and to other flooding conditions and risks.

### A. Advances in Understanding and Actionable Science

In 2015, there was no formal recognition of pluvial flooding in EO 13690, the FFRMS policy, the EO 11988 and 13690 interagency implementation guidance (Water Resources Council 2015), or the CISA Appendix. In fact, the over 2,300 public comments that helped formulate the implementation guidance only mentioned the term "pluvial flooding" once—and that was in the context of other flooding types.

As depicted in Figure 8, the majority of the conterminous United States has a nexus with rivers and coasts, meaning that traditional Federal flood risk management efforts have a corresponding focus on these coastal and riverine areas.

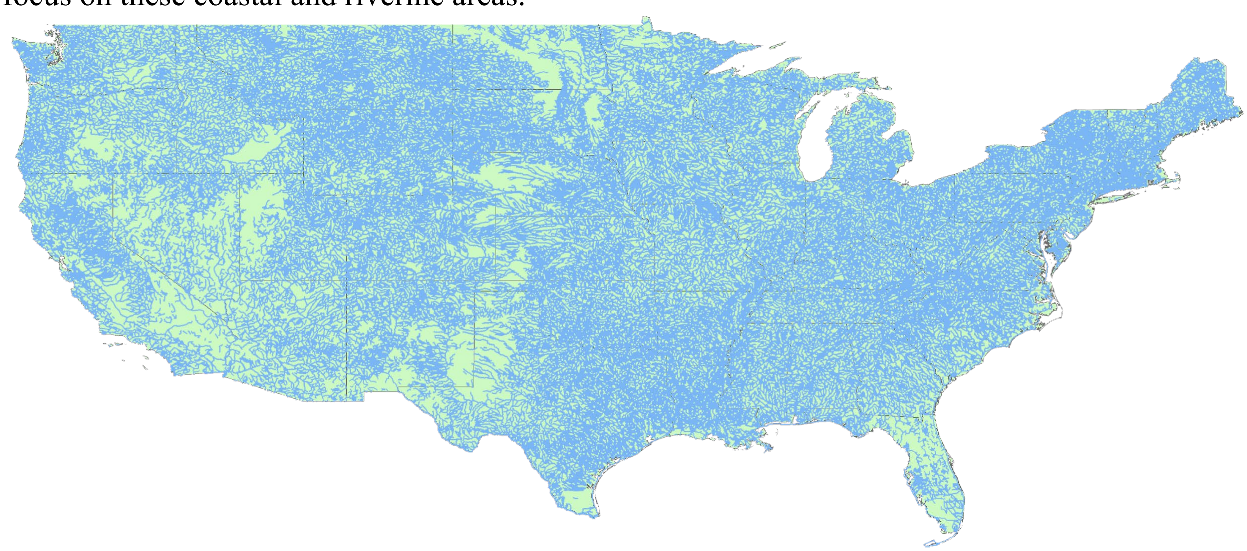

*Figure 8: Rivers and Coasts within the Conterminous United States (FHWA 2022).*

[16] Essentially a "pluvial" managed the risk of getting wet by rain.

The mapping of pluvial flooding is extremely rare in FEMA maps, which complicates flood risk considerations as some planners and engineers do not perceive when their actions are not in the FEMA floodplain. This attitude and assumption is often amplified when pluvial flooding occurs in a field or location well outside "traditional" floodplains.

Additionally, the paucity of such FEMA-delineated areas precludes quantifying pluvial flooding using either the FVA or 0.2PFA under the FFRMS. FVA uses the FEMA BFE as the basis of adding 2 or 3 feet to represent future FFRMS conditions. If there is no FEMA BFE, then this becomes problematic. Likewise, only 20 percent of the United States has FEMA 0.2-percent-annual-chance floodplain maps and information, limiting potential use of the 0.2PFA. This leaves application of CISA as the sole approach that can consistently allow consideration, quantification, and delineation of the FFRMS pluvial floodplain.

### *Advancing CISA Considerations*

Pluvial flooding can be considered a function of two facets in a CISA context: probability and relevant factors. The following sections describe these facets, and their implications to applying CISA for pluvial flooding.

#### *Probability*

The first facet is some rainfall probability associated with a condition. For FFRMS, this condition would be the CISA base flood. Since the CISA base flood consists of projected future circumstances, this rainfall represents the nonstationarity-adjusted, 1-percent-annual-exceedance probability (AEP) precipitation.

Note that this CISA precipitation only applies to that projected future 1-percent AEP. However, climate science recognizes that future rainfall events will occur over the entire spectrum of nonstationarity-adjusted probabilities. For example, climate change rainfall effects may be more noticeable during more frequent events or those considered during partial-duration rainfall analyses. As a result, CISA distinguishes FFRMS-focused pluvial flooding from pluvial flooding over the whole spectrum of potential precipitation events. This distinction has implications for the actionable status of pluvial flooding.

**Important caveats:** The most important takeaway for the probability facet with regard to CISA is the paucity of actionable nonstationarity-adjusted, 1-percent AEP precipitation. As described elsewhere in this report, NOAA NWS has conducted research on applying nonstationarity to their NOAA Atlas 14 precipitation volumes (NWS 2022). However, this research focused on the Northeastern States and has not been validated for other regions of the United States.

Using research conducted under the auspices of the National Academies (Kilgore et al. 2019), the FHWA produced a process and tool to convert readily available downscaled climate data at the local level into relevant statistics for transportation planners and designers (FHWA 2020). This CMIP Tool works with the statistically downscaled CMIP5 (DCHP) Localized Constructed Analog (LOCA) dataset; the LOCA dataset provides statistically downscaled projections to the 1/16-degree resolution. For the purposes of this section, it also includes methods for calculating future return period precipitation. A few issues exist for this approach: first, the daily LOCA climate projections extend over the CONUS as well as Canadian portions of the Columbia River and Missouri River Basins. Unfortunately, this means the DCHP data (currently) excludes Alaska, Hawaii, Puerto Rico, the U.S. Virgin Islands, America Samoa, Guam, and the Commonwealth of the Northern Mariana Islands. More importantly, similar to the NOAA research, the process still needs additional validation to ensure national applicability.

These caveats limit application of this probability element to locations and actions where data can be readily obtained and applied in the CISA context.

*Relevant Factors*

Secondly, and most important for the purposes of pluvial flooding, CISA needs to consider some other relevant factors, including urban settings, land use, interior drainage of flood control structures, certain wetlands and other habitats, and transportation assets. This section will briefly describe each of these factors.

**Urbanized flooding:** Since the 2015 CISA Appendix was written, there has been a growing awareness that pluvial flooding is an emerging consideration of flood risk management within our Nation's urban locations. Two publications, a 2018 report by the University of Maryland and Texas A&M (University of Maryland, College Park and Texas A&M University, Galveston Campus 2018) and a 2019 ASFPM-sponsored Gilbert F. White Flood Policy Forum (Association of State Floodplain Managers Foundation 2019) frame urban flood risk, including pluvial flooding in locations outside those typically found in Federal flood authorities and missions. They captured the differentiation of such urban flooding from a more "traditional" flood risk management focus.

Other studies have focused on modeling aspects of pluvial flooding on surface and subsurface systems such as streets and storm drains. Some of these modeling efforts take advantage of evolving 2D and computational fluid dynamic models described in earlier sections. These models can simulate the effect of the current or future 1-percent-annual-chance rainfall on the street systems of a small metropolitan area.

Yet, the design standard for a majority of these street and storm drain systems applies lesser rainfall frequency than the base flood (American Association of State Highway and Transportation Officials 2014). FFRMS analysts do not need such modeling to intuit that flooding will occur during those smaller events as well— typical practice of designing an urban curb and gutter system for a 10-percent-annual-chance event focuses on that flood risk and does not consider the 1-percent-annual-chance rainfall. Additionally, climate change-induced increases in future rainfall will likely reduce the capacity, and thus resilience, of these systems. The FFRMS provides resilience for the pluvial base flood, but not other pluvial flooding events. Therefore, a CISA focus may not align with the needs of urban systems.

**Land use change:** Land use changes also are factors that may increase flood risk. While pluvial flooding does not directly align with the rainfall-runoff concept relevant to riverine flooding, there may be some direct correlation with such changes. For example, adding traffic lanes to a highway reduces pervious areas that allow infiltration. Elevating a coastal structure on piles may allow the reverse to occur (e.g., more infiltration). Yet, land use changes like these are incorporated more into coastal and riverine flood hazard assessments than pluvial assessments.

**Levees or flood risk management structures:** While levees and related flood structures and facilities provide risk management of riverine or coastal floods, they may also interrupt rainfall runoff, increasing the likelihood of pluvial flooding even when they reduce flood risk overall. In such cases, those areas will likely need consideration of the FFRMS CISA pluvial base flood. As described below, applying the CISA to pluvial flooding in a leveed area will require analysts to apply best professional judgment and local knowledge of site-specific environmental and sociocultural considerations.

The application of such judgment considers how several factors may complicate this special situation in practice, including:

In accordance with the Flood Control Act of 1944 as amended, USACE can generally only participate in flood risk management projects along a natural or modified channel downstream of the point where the 10-percent AEP flood exceeds 800 cubic feet per second (the "800 cfs rule") as outlined in Engineering Regulation 1165-2-21 "Flood Damage Reduction Measures in Urban Areas," dated 30 October 1980. This normally prevents USACE involvement in stormwater drainage projects, which are usually assumed to be a non-Federal responsibility. However, this regulation only applies to "urban areas," which are defined in the regulation but in a way that leaves some room for interpretation. The rule is also evaluated "under conditions expected to prevail during the period of analysis," which may allow for some adjustment for climate change or other changes, at least in theory. Finally, the regulation specifies several exceptions to this rule and a process for requesting an exemption from Headquarters, Department of the Army.

One of the most important exceptions to the rule above applies when a proposed levee would interrupt runoff and cause flooding that would not otherwise occur. As outlined in ER 1105-2-100 "Planning Guidance Notebook," last updated 22 Apr 2000, par. E-18.e., analysis of the net flood risk management benefits of levees should include residual damages caused by interruption of interior drainage. These residual damages may be mitigated by pumping or other means, with the recommended mitigation being that which reasonably maximizes net benefits. As a result, when planning levees that interrupt interior drainage, USACE may participate in projects to reduce pluvial flooding, and may do so up to any level of intervention that is marginally economically justified. When the interior drainage required to mitigate the effects of a levee is not economically justified, USACE may still construct the "minimum facility" needed to return the level of pluvial flood-risk to its pre-levee state.

These rules are complicated further by the fact that in urban areas, when the plan that maximizes net economic benefits does not deliver 90 percent reliability that the probability of flooding is equal to a 1-percent-annual-chance or less, an exception to the requirement to maximize net benefits may be recommended, when certain conditions are met (ER 100, par. 3-3.b.(12) (USACE 2000).

Finally, USACE Flood Risk Management policy allows a categorical exemption from the economically optimal plan when the non-Federal interest desires a smaller plan (ER 100, par. 3-3.b.(11) (USACE 2000), and the non-Federal interest may in certain cases also request a plan that is not marginally economically justified if they agree to bear the incremental cost between the two plans (a "locally preferred plan," ER 100 par. 2-3.f.(4) (USACE 2000).

All of these factors complicate analysis of pluvial flood risk in a changing environment, particularly when Federal agencies and non-Federal interests may have different preferred climate scenarios or standards for actionability of climate science.

**Wetlands and other habitats:** Recognizing the potential flood-hazard attenuation benefits and other environmental services afforded by wetlands and other natural habitats, EO 13690 added the requirement that ''where possible, an agency shall use natural systems, ecosystem processes, and nature-based approaches when developing alternatives for consideration.''

Preserving and restoring wetlands and other natural habitats are actions that have been long-recognized as viable approaches for communities to use in managing flooding in their coastal and riverine floodplains. Some wetlands and natural habitats occur outside of designated coastal and riverine floodplains, in areas susceptive to pluvial flooding; these natural areas can also serve as effective tools in mitigating pluvial hazards. For example, the FHWA provides Federal aid for state departments of transportation to engage in wetland and habitat banking, with acreage located in floodplains that are not associated with riverine or coastal flood sources. Of interest are the water budgets for these locations. Similar to those urbanized examples, these water budgets typically focus on flood frequencies much less than those associated with the FFRMS base flood.

So, while wetlands and other habitats are important in establishing our understanding of hydrologic conditions and can demonstrably provide flood-attenuation and other mitigation benefits for lesser flood events, are these effects significant enough to warrant explicit consideration in application of CISA when considering the future base flood? Additionally, the distribution and function of these habitats may change in response to climate change; how would such changes be considered in a CISA analysis? These uncertainties make application of CISA to assess future pluvial flood hazards particularly challenging. Further work to understand the quantifiable impacts of wetlands and other natural and nature-based features on pluvial flooding—and how those impacts may vary with climate change—will be important in developing actionable science for projecting future pluvial hazards.

**Transportation assets:** Transportation networks have assets subject to pluvial flooding—for example, tunnels and depressed highway segments. Unlike other constituents, they typically have design standards that more closely mirror frequencies associated with FFRMS. These assets represent an opportunity to apply CISA to both characterize their vulnerabilities and to assess the resilience of such assets to future projections. For example, many tunnels have pumping stations to remove these pluvial associated flows. Application of CISA concepts over the remaining service life would allow for a flood risk assessment of those tunnels and pumps.

### B. Roadmap: Needs and Opportunities to Improve Projections

Pluvial flood risks already are present within the United States. On a national basis, it is unknown precisely where the risks of pluvial flooding may occur. Climate change, including sea level rise and increases in precipitation, will increase the occurrence and risks of pluvial flooding in areas and for constituents not currently evident. The major hurdles may not be the precipitation science, but the complexities of the topic area itself. Additionally, there is congruence of pluvial flooding with other flooding and flood risks, such as high-tide and other chronic hazards. This complexity may require additional assessment of how these flood types and risks align with the intent and authorities associated with FFRMS and how they can be integrated with other flood types.

Pluvial floods also pose different (and perhaps more site-specific) risks than coastal and riverine flooding. At this time, at best, CISA can consider pluvial flooding only in limited circumstances. This section has identified gaps and deficiencies in both science and applicability. Clarity is needed in the context of pluvial flooding and associated research and data development.

## VI. Assessing Future Compound Flooding

Floods can be caused by various mechanisms, individually or in combination. In Brazil, a country exposed to relatively few other natural disasters but plagued by frequent floods, at least five different words are used to refer to floods, each specifying a different character or generating mechanism.

Despite the varieties of floods, a typical flood frequency analysis, including those performed in the interest of delineating a floodplain or other hazard area, usually addresses a single source or cause of flooding. Nevertheless, it has long been recognized that floods may be caused by a combination of factors, even if none of those factors would have led to an extreme flood event on its own. One long-studied and common example is a confluence of two streams; another is an elevated water level in the receiving water body of a drainage system coinciding with heavy local runoff. Recently, concern about and interest in the likelihood of simultaneous riverine floods and coastal surges has grown, with events like Hurricane Barry (2018) and Tropical Storm Cristobal (2019) bringing this possibility into greater public awareness.

A related phenomenon is the existence of mixed populations of floods, where a record of floods includes events caused by two or more physical processes, though they may not occur simultaneously. In areas subject to both rainfall and snowmelt, or those exposed to tropical and non-tropical rainfall, a proper analysis of the probability of floods must allow these populations to be separated, considered individually, and then re-combined using appropriate statistical methods. Some of these systems may be subject to both mixed populations and compound floods, such as a flood caused by rain-on-snow.

Another concept related to compound flooding is the treatment of total water levels as the sum of various components. This is a common approach to flooding in coastal areas, which are subject to inundation due to combinations of processes including sea level, tide, storm surge, wave action, and others. Combining these components into a total flood elevation requires some assumption of the statistical correlation between components. Typically, components are assumed to be either statistically independent (such as tide with surge) or perfectly correlated (such as waves and surge). While the assumption of perfect correlation among components is conservative, it is usually not excessively so, because surge and waves are both caused by storm winds (and much of what is commonly called “surge” is in fact wave setup). An illustration of the component approach to floods is provided in Figure 1, and further information is provided in Section III on coastal flooding. While combining component processes into a flood height requires making assumptions about the statistical relationships between components, it is not generally considered an example of compound floods as covered in this section.

Historically, methods for analysis of compound (also known as coincident, simultaneous, or joint) floods, as well as those for analysis of mixed populations, relied on the assumption that the underlying flood-generating mechanisms were statistically independent. This was because, while mathematical methods exist for treatment of partially correlated forcing mechanisms, data availability was usually insufficient to establish the nature of that correlation with confidence. Recently, new approaches have been developed that are beginning to allow a fuller treatment of compound floods, as described in the following subsections.

## A. Advances in Understanding and Actionable Science

In 2015, compound events received a brief mention in the CISA Appendix. Specifically, Section III. E. of the 2015 CISA Appendix focused on compound fluvial/coastal floods in estuarine areas, stating that these events can be expected to change in frequency as sea levels (or lake levels in the case of the Great Lakes) change due to the impacts of climate change. It also stated that observed frequency of compound floods had increased and that this increase may be expected to continue because all areas of the country are expected to experience increased frequency and intensity of rainfall (Federal National Climate Assessment and Development Advisory Committee 2014), and the frequency and intensity of the strongest North Atlantic hurricanes had also been observed to increase.

Since 2015, understanding of compound floods has expanded beyond just fluvial/coastal floods in estuaries. A growing body of literature now recognizes compound floods as a subset of compound events, which has gained acceptance as a broad area of research deserving of dedicated study (Nature Climate Change Editorial Board 2020). Zscheischler et al. (2020) propose a typology of compound events comprising four categories: preconditioned, multivariate, temporally compounding, and spatially compounding. Under this typology, preconditioned events include those where one event sets the conditions for the second (or third, or later) event to be more extreme or destructive than it would have been otherwise. Heavy rain on deep snowpack would be one example, as would a rain event on soil saturated by a previous storm. Multivariate events include the fluvial/coastal compound floods mentioned in the 2015 CISA Appendix, as well as simultaneous drought and heatwaves and damaging combinations of wind and precipitation. Temporally compounding events refer to clusters of events of the same type or cause occurring in rapid succession, causing more damage and more management challenges than if they had occurred with a more typical spacing; a compound flooding example might include climate modes such as the El Niño/Southern Oscillation causing repeated heavy rain events to increase flood depth and damage. Finally, spatially compounding events are those where impacts are increased by virtue of multiple events impacting distinct but connected locations. A contemporary example might include a flood occurring during a pandemic, as with 2021's Hurricane Ida. Social distancing became impossible as the more immediate emergency of flood-damaged housing forced large numbers of people into mass emergency shelter, complicating the response to both emergencies. A simpler example might be numerous spatially distinct events overwhelming the response and recovery resources of a region, as occurred with California's wildfires in 2020.

To address the unique considerations posed by compound events, Raymond et al. (2020) argue that they deserve focused research by the climate science community, as well as dedicated attention on the parts of the policy- and decision-making communities. The lack of observational data on these events, even relative to extreme individual events, as well as nonlinear feedback and unknown tipping points, mean that their management requires different approaches and more collaborative efforts than do individual events. They also argue that responses should be informed by the "decision space" of the event type, including its spatial and temporal scale.

With so many types of compound events, and an ever-expanding body of literature describing them, it is arguably even more difficult now than in 2015 to specify exactly what is meant by the term "compound flooding." As a result, it is imperative that a clear definition be established to guide development of agency-specific technical guidance for implementation of the CISA in areas subject to these floods, and focus research needed to address remaining critical knowledge gaps. Having a standard definition may also help reduce confusion between this topic and related topics, such as mixed populations or component-based approaches.

### *Established Approaches*

As a subset of compound events, compound floods may be among the most studied event types, though much more research is needed. While new methods and research have emerged since the

2015 CISA Appendix was written, few have reached the standard of actionability, so the approaches described in this section will typically be the ones upon which the CISA analyst will rely. Traditional approaches to compound flooding generally relied on one of two approaches: conservative assumptions or total probability methods. An example of a conservative assumption for water surface elevations may be found in the U.S. Army Corps of Engineers' Engineering Manual (EM) 1110-2-1416, "River Hydraulics" (USACE 1993b). Paragraph 6-8.f. of this manual states that "When the profile computation begins at the outlet of a stream influenced by tidal fluctuations, the maximum predicted high tide, including wind-wave set up, is taken as the starting elevation at a station usually located at the mouth of the stream." While no definition is provided for the "maximum predicted high tide, including wind-wave set up," one approach may employ a high astronomical tide condition such as mean higher high water plus a conservatively high estimate of coastal surge and/or water elevation due to waves. An even more conservative assumption might include using the highest astronomical tide of the entire tidal cycle. Ambiguity in this case allows for use of best professional judgment.

A more rigorous approach to estimating the risk of compound floods relies on the total probability theorem. This approach is recommended in both Chapter 11 of EM 1110-2-1415, "Hydrologic Frequency Analysis" (USACE 1993a) (Figure 9) and EM 1110-2-1413, "Hydrologic Analysis of Interior Areas" (USACE 2018). In the first case this method is applied to the confluence of two streams, in the second to an interior drainage system discharging to a water body of variable elevation and thus backwater effect on the drainage. This method requires the user to compute a frequency-exceedance function (relating stage or discharge to probability of exceedance) for one of the two forcing variables, and a stage- or flow-duration function for the other (describing the percentage of time when a given condition is exceeded). Importantly, the user must determine which of the two variables is the "more influential" variable to be addressed with the frequency-exceedance curve and which is the "less influential" to be considered using the duration curve. The user then simulates many combinations of the two variables with a hydraulic model, generating a response matrix yielding flood heights for each combination of conditions. Families of conditional-probability curves are then generated, describing the probability of exceedance for a given flood height given a particular value of the less influential variable. Finally, the total probability theorem[17] is used to sum these curves into a single overall stage-frequency curve. This method is implemented in several common statistical software packages, including the U.S. Army Corps of Engineers' Hydrologic Engineering Center Statistical Software Package (HEC-SSP) (USACE n.d.).

Importantly, the method described above must be performed for every location along the river or other water body where a flood height of a given probability of exceedance is required. It is also common for the "more influential" and "less influential" variables to be reversed as one moves along a river profile, as the backwater effect of a downstream water body becomes less important toward the headwater of the stream and the river flow becomes less important toward the mouth. EM 1110-2-1415 recommends that in this case, the method be performed both ways, generating an envelope where the higher of the two profiles governs at any given point (under the logic that the higher of the two profiles would reflect the correct choice of the "more influential" variable).

[17] The total probability theorem, or law of total probability, states that the probability of an event A is equal to the probability of A given event B multiplied by the probability of B, often written as $PA=\sum PBP(B)$.

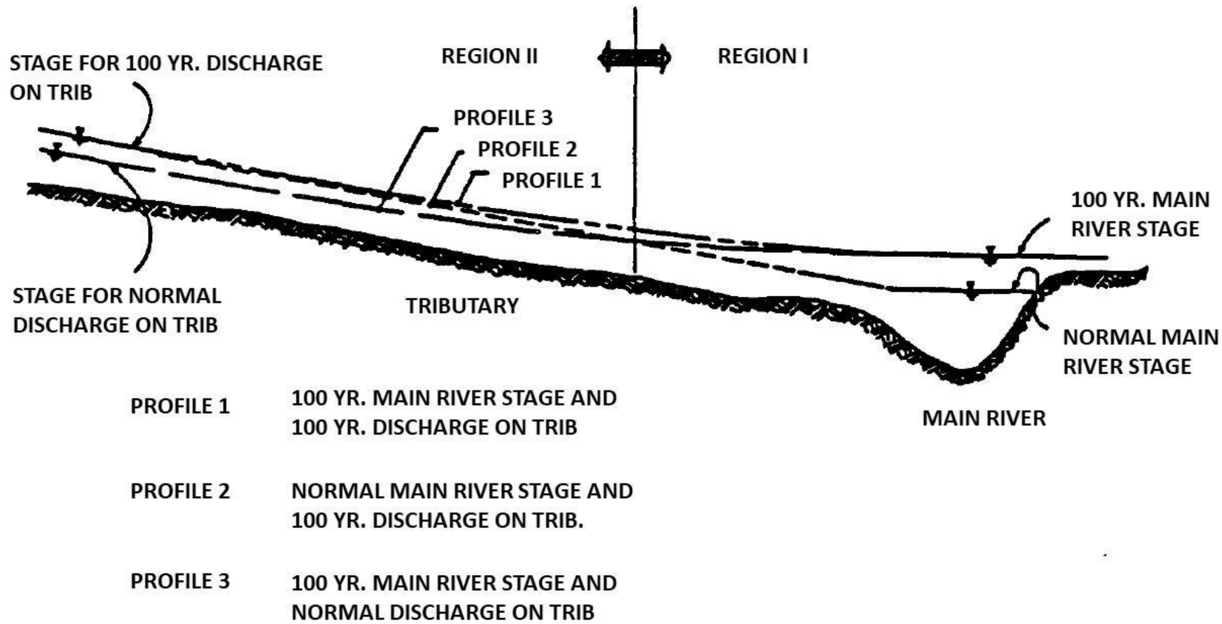


*Figure 9: Illustration of river flood profiles for various combinations of main river and tributary flows, showing regions of more and less influence of each variable (Figure 11-1 from EM 1110-2-1415 (USACE 1993a))*

While the total probability theorem allows for consideration of variables that are not statistically independent, in practical terms this approach is limited to situations where the assumption of independence is reasonable, because most streamflow records are not long enough to allow for a confident estimation of correlation among variables. Even in those rare cases when a long enough record is available, as on some major rivers of Europe or Asia, one might question whether the entire record was representative of present conditions.

An extension of this general method for situations where insufficient observational data exist to estimate the probability of some combinations of factors, relying upon synthetic data generated by simulation of events, is known as the joint probability method with optimal sampling (JPM-OS; Toro et al. 2010). This approach has become commonplace in estimation of hurricane storm surges, which are rare events and depend on at least five variables: storm forward speed, landfall location, storm track angle relative to the coastline, central pressure deficit, and radius to maximum winds (and antecedent water level, which may be an additional variable). This method is potentially applicable to compound floods, and research is ongoing to extend statistical modeling of storm surges into areas subject to compound flooding.

A final, very simplified approach merits a brief mention. Computing two (or more) flood elevation profiles based on individual flood-generating mechanisms, and then adopting the highest of these at any given location, i.e., the pointwise maximum, is probably the simplest possible approach to estimating the risk of compound flooding. However, as demonstrated by Moftakhari et al. (2019), this approach may seriously underestimate flood risk in the transition zone where multiple mechanisms are influential (though it is likely adequate outside that zone). We do not recommend this approach for implementation of the CISA or FFRMS.

Despite the shortcomings associated with the assumption of statistical independence between flood-generating mechanisms, the total probability approach (possibly supplemented by synthetic data as under the JPM-OS) remains the best actionable approach to estimating the probability of compound floods. New methods, some of which are described in the following subsection, are under development that may soon improve these estimates, but they have not yet been sufficiently vetted in the research community or employed in engineering practice to meet the standard for actionability. Therefore, actionable science and practice for compound flooding remains the same as was recommended in the 2015 CISA Appendix. In particular, agencies should begin with analysis of coastal future flood elevations, including sea level change, to properly account for backwater effects in coastal areas subject to compound flooding. Potential changes to fluvial and pluvial flood hazard due to climate change or other changes may also be considered, but at this time are generally less certain than sea level change.

### *Advancing CISA Considerations*

Improvements in the estimation of compound flood risk generally fall into two categories: new statistical approaches and improvements in modeling practice. One promising statistical approach is the use of copulas to estimate the dependency of flood-generating mechanisms rather than relying upon the assumption of independence. A copula is a multivariate cumulative distribution function describing the dependence between two variables. The application relies upon Sklar's theorem that a multivariate joint distribution may be written in terms of the univariate marginal distributions of each variable and a copula describing the dependence between those variables (Sklar 1959).

In the past decade, copulas have been applied to compound flooding analyses, beginning with analyses of flooding near the confluence of two streams (Kao and Chang 2012; Bender et al. 2016). Many different copula functions exist, and the question of the best fitting function in the general case remains an open problem. Given a set of candidate models, one approach is to identify a relatively best-fitting selection using a model selection criterion such as the Bayesian information criterion or Akaike information criterion. As with the choice of a "more influential" and "less influential" variable described in the section above on the total probability method, the user must first model one of the marginal probabilities conditioned upon the other or vice versa. In the method described by Bender, however, there is no choice of which direction to condition: the user will always do both and then use the maximum of the two. Any number of combinations of variables may cause a flood with the same probability of exceedance, as shown by the isolines in Figure 10 below. For any of the dark lines, any point lying on that line has the same probability of exceedance, though they are caused by different combinations of forcing variables. For any such flood event, there is a single combination of variables that is most likely to occur, as shown with the red dots. This leads to the paradoxical-sounding fact that while there are an infinite number of ways to get a 1-percent-annual-chance compound flood, some 1-percent-chance floods are more likely than others.

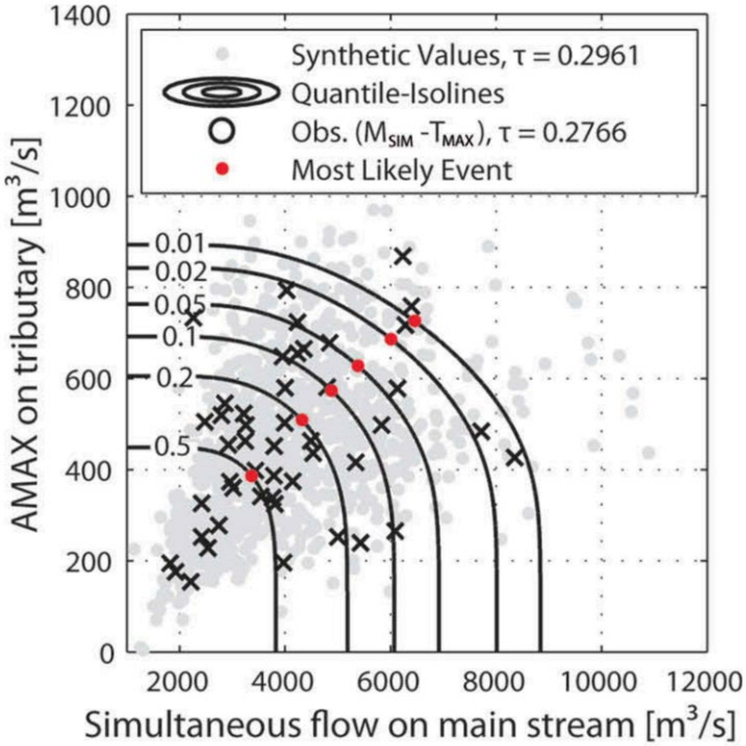


*Figure 10: Isolines of equal flood probability (and height) for various combinations of discharge on a main stream and a tributary (from Figure 6 of Bender et al. 2016)*

Because either of two forcing variables that lead to a compound flood may be conditioned upon the other, two sets of isolines must be created, leading to an envelope as shown in Figure 11. This envelope describes the conditions that should be used for determining the flood elevations in the area of interest.

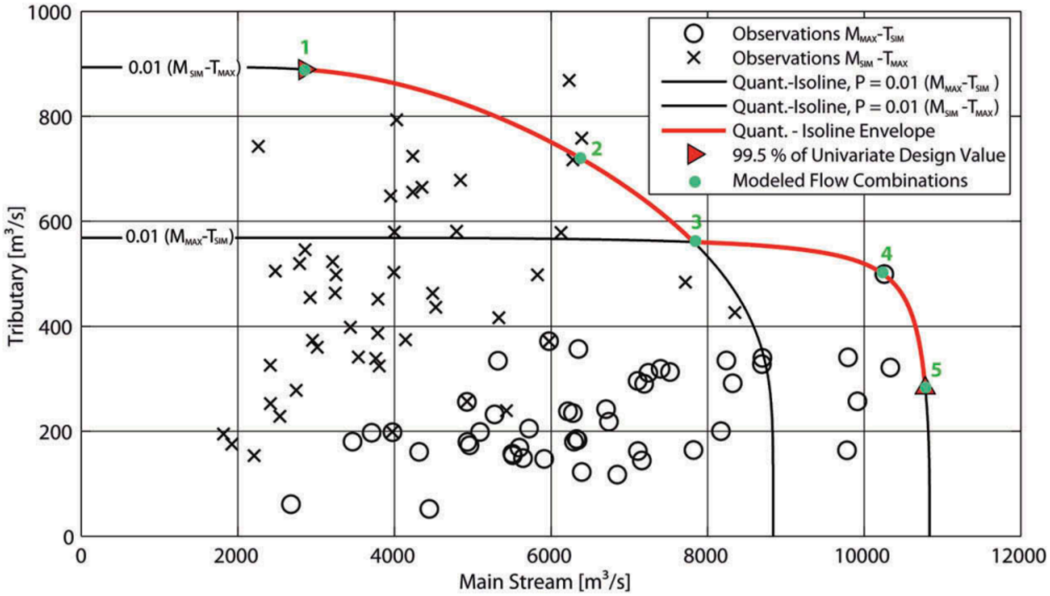


*Figure 11: A probability envelope (red line) composed of the pointwise maxima of two isolines (dark lines) each with a 1-percent-annual-chance of exceedance (from Figure 7 of Bender et al. 2016)*

The copula approach can also describe the uncertainty of flood frequency estimates, and can be extended to more than two variables if needed. As this method gains wider adoption in the scientific community, agencies may consider developing detailed technical guidance for how it should be applied to their needs.

Improved statistical techniques offer promise for developing more accurate estimates of the probability of multiple flood-generating mechanisms occurring together, but the resulting flood height and extent still require the use of hydraulic and/or hydrologic models to develop the response matrix. Computational modeling of compound floods is complicated by several factors, including the lack of observational data from past compound floods for model calibration and validation. The complex physics of compound floods can also be a challenge, particularly when flood-generating mechanisms are physically distinct, as with fluvial/coastal floods.

Model coupling describes the process of joining multiple models together for the purpose of simulating events for which any individual model would be insufficient, such as a river model and a coastal storm surge model. Santiago-Collazo et al. (2019) provide a review of coupling techniques for fluvial/coastal flood modeling and offer four categories. One-way coupling refers to running one model to generate the boundary conditions for another, then running the second model under those conditions. Loose coupling is an iterative process where one-way coupling is performed, then the second model outputs are used to generate boundary conditions for the first model, which is then re-run, with this process repeated until convergence is reached. Tight coupling involves two models run simultaneously within a single computational framework, with elements of each model's code incorporated into the other. Finally, full coupling describes the creation of a single model with sufficient mathematical complexity to simulate all the physical processes that lead to compound flood. These more complex models will frequently require supercomputers or distributed computing, so the choice of technique will depend on available time and resources as well as the required level of detail and the consequences of inaccurate results.

Furthermore, a model with higher computational cost will allow less opportunity to evaluate numerous scenarios, including future climate scenarios, so model accuracy must be balanced against runtime if multiple scenario and/or Monte Carlo approaches are to be used.

At this time, one-way coupling is commonly employed, as when an Advanced Circulation (ADCIRC) model is used to simulate storm surge as a downstream boundary for a River Analysis System model. Some tightly coupled modeling frameworks also exist, such as the ADCIRC+SWAN (Simulating Waves Nearshore, a wave model for shallow environments) framework for modeling storm surges and coincident waves. Research is now focused on developing more loosely coupled models, such as the framework under development at the Engineer Research and Development Center's Coastal and Hydraulics Laboratory (ERDC-CHL) depicted in Figure 12. Finally, some approaches may blur the lines between these categories. For example, the Semi-Implicit Cross-Scale Hydroscience Integrated System Model (SCHISM) is a framework of tightly-coupled but interchangeable modules which operate as a single, fully coupled model (Zhang, et al., 2016).

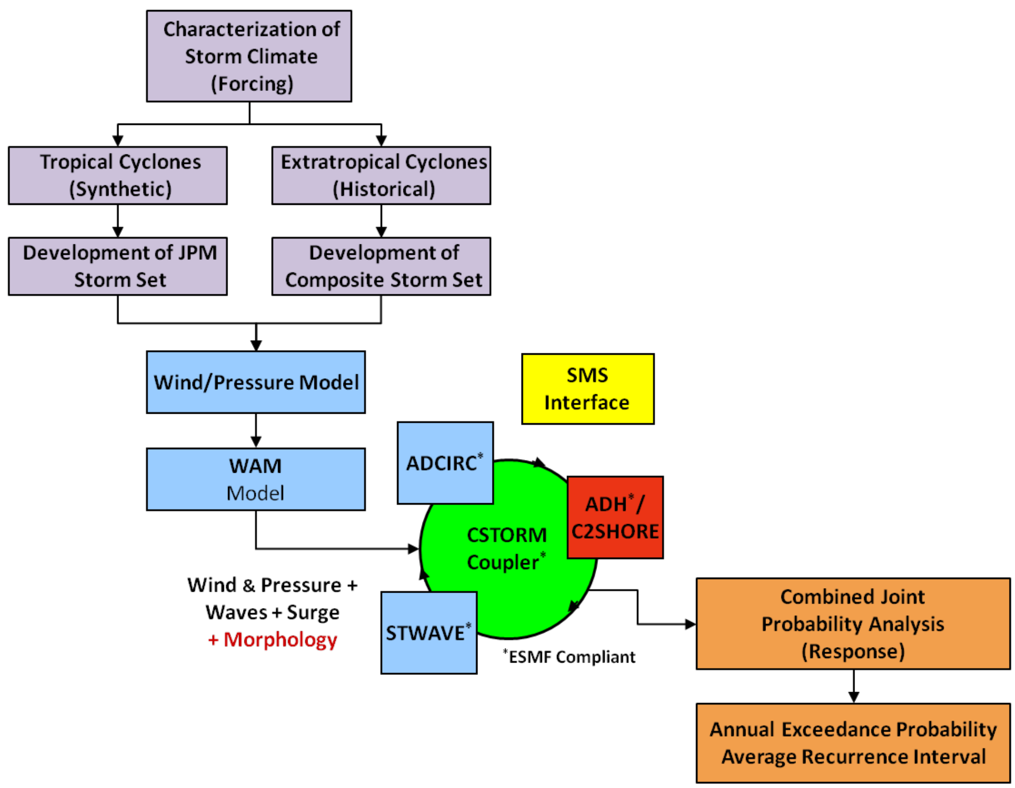


*Figure 12: A loosely coupled modeling framework under development at ERDC-CHL for simulation of coastal floods (courtesy of ERDC-CHL)*

While these recent developments in statistical and numerical modeling offer promise for the estimation of compound floods, the state of the science is changing rapidly, and some of the emerging methods discussed here may reach the level of actionability prior to the next update of the CISA State of the Science report. There is therefore a need to monitor research and development in academic fields, U.S State and local governments, and agencies with an eye towards future methods and tools. As these methods reach the level of actionability, agencies should consider developing guidance to incorporate them.

### B. Roadmap: Needs and Opportunities to Improve Projections

Future needs for analysis of compound flooding within the CISA include further development of statistical models, including modeling of the seasonality of floods to assess the likelihood of simultaneous forcings, and to detect trends or sudden changes in flood seasons, whether due to climate changes or other changes. More sophisticated numerical models are also needed to properly represent the complex physics that cause compound floods and simulate them efficiently so that climate change scenarios can be considered without having to prematurely select among potential futures. Methods are also needed to enhance the utility of simulations based in large ensembles of process-based models incorporating climate projections, for estimation of present and future compound flood hazards. These advances may include techniques to accelerate computation time, improve downscaling and bias correction, select ensemble members based on process fidelity or other metrics, or other enhancements to reduce the range of uncertainty associated with a wide range of ensemble members, without implying false precision.

## VII. Identifying Future Flood Hazards in Areas without a FIRM or BFE

### A. Advances in Understanding and Actionable Science

Implementation of CISA can be challenging if there is a lack of available flood hazard information. Appendices B and C of the interagency implementation guidelines for EOs 11988 and 13690 (Water Resources Council 2015) specifically address cases of areas that do not have a FEMA-produced BFE, and some options of where to source best available data when a FEMA BFE is not published. This can be particularly challenging on Federal lands, as these lands are not mapped as part of the NFIP. It is important to recognize that a lack of defined BFE or FIRM reflects the needs and prioritization of implementing the NFIP and is not necessarily indicative of a lack of available data. Often, data are available either from FEMA or other sources. For example, FEMA coastal mapping stillwater data are largely available for CONUS coastal areas as part of regional study data but may not have been mapped as part of a FIRM due to the needs of the NFIP.

### B. Roadmap: Needs and Opportunities to Improve Projections

Areas without a FEMA FIRM or BFE can present a challenge to the implementation of CISA. Looking towards the future, there is a need to both better understand this challenge, as well as work towards a future state where comprehensive flood hazard data are accessible everywhere. In support of these needs, there are short-term actions that could greatly support data accessibility, in addition to long-term data development to fill the known gaps.

The roadmap towards this state can be summarized with the following main components:

- Understand the scope of the challenge and updating FEMA metrics to account for all areas, including those outside of CONUS.
- Consolidate and facilitate ease of access to existing flood hazard information beyond FIRMs.
- Identify interagency needs for published FIRMs and BFEs, and coordinate with FEMA on opportunities to address them.

- Conduct interagency work towards the development of comprehensive non-FIRM flood hazard data.
- Integrate the CISA approach using workflows discussed in prior sections.
- Work with Canada and Mexico to develop harmonized data necessary to model and map future transboundary flood hazards.

Research, development, and related efforts to refine datasets, models, and other products called for in this roadmap would yield comprehensive, forward-looking flood hazard data for the Nation.

## VIII. The Path Forward and Conclusion

This 2023 CISA State of the Science report is intended to present accurate and actionable scientific advances in climate change and other flood risk changes. This report may inform recommendations from the Mitigation Framework Leadership Group to update the FFRMS in the future. This report was conducted under the auspices of the National Climate Task Force's Flood Resilience Interagency Working Group and in consultation with agencies who participate in the Federal Interagency Floodplain Management Task Force. Additional state of the science reports will likely be necessary in future years, as the body of knowledge on the impacts of climate change and other processes (e.g., land use change and geomorphic change) on flood hazards expands and improves over time.

In the time between periodic science assessments, sustained and coordinated action is needed to address the myriad data, modeling, mapping, and integration needs identified across the roadmap subsections of this document. These needs are well beyond the capacity of a single agency or program to address. Further, many current research, development, and service-provision activities underway across the Federal Government, including new efforts funded by the Infrastructure Investment and Jobs Act of 2021 and the Inflation Reduction Act of 2022, will contribute significantly to the science underpinning projections and management of both current and future flood hazards. Existing interagency science-coordination bodies—such as the Interagency Council for Advancing Meteorological Services (ICAMS), USGCRP, and the NOAA-led Integrated Water Resources Sciences and Services collaboration—currently consider and focus to varying degrees on flood science, typically as one in a long list of priorities directed by their respective guiding statutes or charters.

Advancing and ultimately addressing the array of science, engineering, mapping, and hazard visualization gaps identified in this report would benefit greatly from establishment of a standing body focused on future flooding, including but not limited to FFRMS requirements and applications. A community of practice (CoP) on future flooding, potentially embedded within one of the groups named above, and following other CoP models with participants beyond the Federal government (e.g., academia, private sector), could be vital in helping agencies retain the knowledge gained through the development of this State of the Science report on both current capabilities and the challenges that users face in applying actionable science for the FFRMS. A CoP could also carry forward the understanding of the principles, strategies, and considerations underlying FFRMS implementation, using it to coordinate agency-level action on the short-, medium-, and long-term roadmap elements described in this report. Finally, a CoP could serve as a focal point for coordinating engagement with those applying the FFRMS (e.g., across Federal, U.S. State, Tribal, Territorial, and local government agencies and the private sector) and in evaluating the efficacy of FFRMS-related science and services. Such feedback could inform Federal science and technology investments, as well as future state of the science report findings and roadmaps for action.

# Appendix A

## CISA Roadmap Items: Future Needs to Improve CISA Implementation of FFRMS

Information below follows the format of this State of the Science report, organized first by flood hazard type (coastal, riverine, pluvial, and combined hazards) and then subdivided by elements (phases) in the respective workflows (for coastal and riverine only). The lists below are not prioritized.

### Coastal Roadmap

#### ELEMENT 1: PROJECT PLANNING AND AGENCY CONSIDERATIONS

- Continue to improve guidance on selection of appropriate sea level rise scenarios, return periods, and time frames.
- Develop more specific guidelines for multi-scenario project analysis including calculation of risk tolerance vs. project life.
- Evaluate reliability for projects of different service lives under changing conditions.

#### ELEMENT 2: CLIMATE AND OTHER ENVIRONMENTAL CONDITIONS

- Continue and expand monitoring of individual factors that contribute to sea level rise (ex. satellite tracking of ocean levels and ice sheet thickness), and long-term tide gauge records.
- Develop better spatial and temporal vertical land motion rates to refine local SLR projections.
- Reduce uncertainties in how well scientists can resolve regional differences in MSL across different U.S. regions.
- Continue to better constrain the models with respect to ice sheet processes.
- Resolve climate-driven shifts in ocean circulation patterns that contribute to RSL differences.

#### ELEMENT 3: STILLWATER ANALYSIS

- Develop national satellite-based VLM maps to improve access to spatial variability in land motion for factor-of-safety considerations in design elevations or obstruction heights, and to enable widespread localization of sea level trend projections.
- Reduce the uncertainty in how climate change will translate to water level impacts on the Great Lakes.
- Further develop a basis for understanding how climate change has impacted Great Lakes water levels through attribution studies that build a narrative.
- Improve regional climate modeling by incorporating better representation of the Great Lakes and their influence using 3-dimensional lake models.

### ELEMENTS 3 and 4 (cross-cutting issues): GEOMORPHIC CHANGE and COASTAL MANAGEMENT

- Establish a validation procedure for geomorphic change modeling that can account for uncertainty and sensitivity.
- Develop more uniform validation and uncertainty analysis through collaborations or meetings bringing a range of academics together, including researchers in other sectors. Promote validation methods in grants requirements.
- Create methods to account for human-made structure or maintenance effects on coastal morphology in both physical and data-driven models.

### ELEMENT 4: WAVE EFFECTS

- Develop and provide metrics and guidance associated with a qualitative or semi-quantitative estimation of future overland wave conditions to better inform the estimation of future high-hazard areas in the short-term.
- Utilize direct analysis and a scenario-based approach to provide comprehensive future conditions related to wave hazards with the incorporation of all wave-induced hazard conditions.
- Conduct research to address Alaska's data paucity and geographic isolation from many national marine and coastal modeling efforts that creates added barriers to assessing changes in significant wave height and extreme water levels associated with the CISA coastal workflow. The added role of changes in the extent and composition of sea ice are an important consideration in assessing coastal flood risk, but research is needed to incorporate future sea ice projections into scenarios and recommendations.

### ELEMENT 5: DATA SHARING AND VISUALIZATION OF COASTAL FLOOD HAZARD INFORMATION

- Develop a bridge product to determine if future Federal actions will occur in the future 1-percent floodplain as a result of climate change and/or sea level rise. These maps will not only need to show the future horizontal extent of flooding, but also the vertical change (future BFE).
- Develop maps similar to DFIRMs for consistent application of the FFRMS. Data that may be produced as part of the FFRD framework may be able to provide future flood hazard and risk in a probabilistic manner that can inform agencies of not only in-and-out status but also percent-likelihood of inundation.
- Evaluate purchase of private sector future conditions data.

## Riverine Roadmap

### ELEMENT 1: PROJECT PLANNING AND AGENCY CONSIDERATIONS

- Project framing: Provide initial guidance on selection of appropriate climate change scenarios, return periods, and time frames.
- Scenario analysis: Develop guidelines for multi-scenario project analysis.

- Service life impacts: Evaluate reliability for projects of different service lives under changing conditions.

### ELEMENT 2: CLIMATE AND OTHER ENVIRONMENTAL CONDITIONS

- Stationary precipitation IDF curves: Complete active NOAA Atlas 14 studies.
- Future IDFs: Incorporate non-stationarity analysis into future IDF formulation with consideration of changes in antecedent conditions.
- Non-climatic scenarios: Identify land use scenarios fit for use in projections.
- Climate-change impacted IDFs: Develop new hydrometeorological atlases ("Atlas 15") to incorporate global climate model simulated IDF data. Ensure that nonstationary methods capture and extend precipitation trends based on the latest precipitation gauge observations and incorporate projected future precipitation from climate models.
- Coherent climate and land-use scenarios: Designate a set of coherent climate and land use change scenarios.

### ELEMENT 3: STREAMFLOW (HYDROLOGY)

- Stationary flood-frequency analysis: Adopt B17C for computation of FFRMS 1-percent AEP plus freeboard and 0.2-percent AEP options.
- Flood statistics: Interagency efforts needed to estimate and disseminate future conditions peak-flow statistics for gauged and ungauged locations throughout the Nation for subsequent use by agencies performing CISA analysis. This would likely be developed incrementally and updated as improved data, models and methods become available.
- Mixed populations analyses: Develop and adopt "B17C style" consensus guidance for analysis of "mixed populations" in flood records, including storm typing.
- Flood scenarios: Evaluate methods for developing riverine flooding scenarios.
- Adopt nonstationary flood frequency analysis guidelines: Develop and adopt "B17C consensus style."

### ELEMENT 4: FLOW, LAND, AND CHANNEL INTERACTIONS (HYDRAULICS)

- Hydraulic modeling: Encourage agencies to use multi-dimensional models.
- Channel change hazard mapping: Consider how Vermont, Indiana, New England States, and Washington regional fluvial erosion hazards mapping techniques could be applied nationally.
- Channel change hazard mapping: Consider automation of methods for reach-scale mapping of all potential types of flood-caused channel changes that include degradation, channel widening, and aggradation (i.e., potential USGS StreamStats application).
- Topobathy data: Grow availability of high-resolution LiDAR and channel topobathy (seamless topographic and bathymetric) data.
- Incorporate flood-related changes, including from climate change scenarios and hydrologic and hydraulic modeling.

### ELEMENT 4: CHANNEL CHANGE SCIENCE

- Understand how drivers of land use and climate cause channel change to better inform riverine hazard management and mitigation strategies. Specifically:
  - How do changes in flood characteristics affect flood energy and related erosion potential and bankfull dimensions and how does this translate to increases in meander-belt width;
  - How can high-resolution hydrography be used to further define headwater channels prone to erosion; and
  - How can agencies incorporate multi-year remotely-sensed digital elevation models, such as those from repeat aerial LiDAR surveys, to document and quantify zones of channel change, including headwater degradation, lateral migration, and aggradation.

### ELEMENT 5: DATA SHARING AND VISUALIZATION OF RIVERINE FLOOD HAZARD INFORMATION

- Data sharing and visualization: Establish prototype for communicating both inundation and channel change risk.
- Flood inundation maps for Federally-owned lands: Consider pilot project to map inundation of agency-owned lands using NWS NWM and CONUS 404 simulations.
- FEMA's Future of Flood Risk Data Initiative: Effort underway to develop new FEMA flood-risk mapping products and datasets for the Nation using probabilistic modeling techniques.

## Compound Flooding Roadmap

- Develop new or updated statistical models, including modeling of the seasonality of floods to assess the likelihood of simultaneous forcings, and detect trends or sudden changes in flood seasons, whether due to climate changes or other changes.
- Develop more sophisticated numerical models to properly represent the complex physics that cause compound floods and simulate them efficiently, particularly in a changing climate.

## Pluvial Flooding Roadmap

- Identify areas subject to localized pluvial flooding on a national basis.
- Improve understanding of how climate change, including sea level rise and increases of precipitation, will impact the occurrence and risks of pluvial flooding in areas and for constituents.
- Improve understanding of the congruence of pluvial flooding with other flooding and flood risks (compound flooding), such as high-tide and other chronic hazards.

## Unmapped Areas Roadmap

- Understand the scope of the challenge and updating FEMA metrics to account for areas outside of CONUS.
- Consolidate and facilitate ease of access to existing flood hazard information beyond FIRMs.

- Identify interagency needs for published FIRMs and BFEs, and coordinate with FEMA on opportunities to address them.
- Conduct interagency work towards the development of comprehensive non-FIRM flood hazard information.
- Integrate the CISA approach using workflows that discuss coastal and riverine flooding.
- Work with Canada and Mexico to develop harmonized data necessary to model and map future transboundary flood hazards.

# Appendix B

## Interpretation of Flood Hazards Under Nonstationary Conditions

In situations when flood hazards are changing over time, the CISA analyst is faced with a question of *when* in time they would like to convey this risk. Figure 13 depicts a simple example where the flow associated with a 1-percent annual probability of exceedance is increasing over time. In such a situation, should the CISA yield the flood elevation and extent associated with conditions at the time of analysis (grey line)? This would give the floodplain user the best representation of the level of risk at the time of publication but would underestimate the true hazard beginning immediately afterward and continuing through the end of the period of analysis (2050, in this case). Or should the CISA yield the worst-case depiction of flood hazard over the analysis period (the green line), even if this would overstate risk for all other times?[18] In most cases, this is the desired outcome. Using the worst-case conditions over the period of analysis ensures that the communicated risk is applicable over the entire period. In other words, this approach may err on the side of being overly conservative but will never permit an understanding of risk that is less than the true value considering the flood hazard projections for the future period.

In some cases, however, a depiction of hazard which integrates its trajectory of change over time may be desired. In this case we use the word “integrate” in the mathematical sense, because the desired outcome is the expected value of overall hazard over the period of analysis, in other words, the integral divided by the range. This is represented by the red line and corresponds to the level of hazard which preserves the correct flood *expectancy* over the analysis period: it tells the user *how many* floods of a given magnitude they should expect to experience over the period 2020-2050, or equivalently, the probability of experiencing *at least* one flood of a given magnitude over that period.

[18] Note that, in cases where the hazard is decreasing over time, the worst-case condition and the initial condition will be equal.

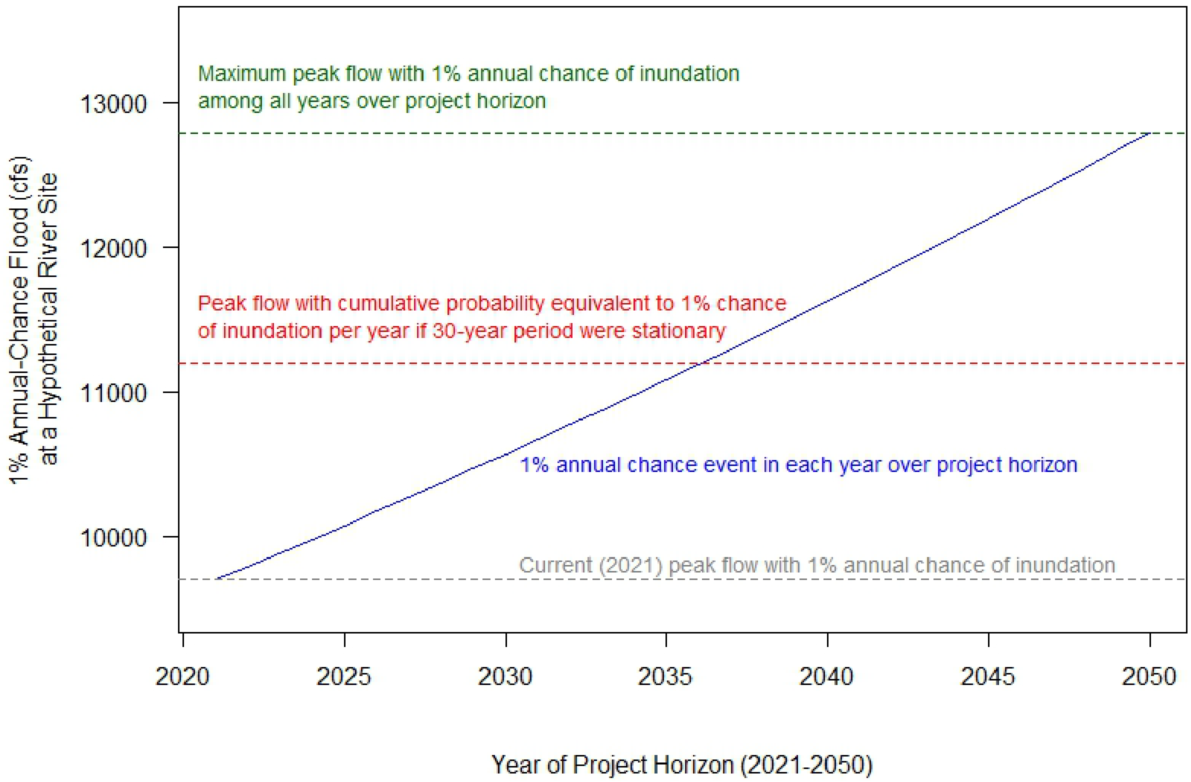


*Figure 13. Three possible definitions for the 1-percent AEP flood (green, red, gray) when flood hazards are changing over time (blue) at a hypothetical river site.*

Situations which may call for this definition of integrated flood hazard and risk assessments include computation of expected flood damages, which may be useful for pricing of financial risk-sharing instruments such as insurance policies or catastrophe bonds. Another common use is in evaluating whether to invest in flood-management infrastructure, the benefits of which may be estimated as the difference in flood risk between the with- and without-project conditions. To determine the integrated risk over a period of interest, the user must first determine the cumulative risk of at least one event over that period, via the binomial distribution:

$$P_n = 1 - (1 - P(x))^n \quad (1)$$

where $P_n$ is the probability of at least one flood in $n$ years,[19] and $P(x)$ is the probability of experiencing one such flood in a single year. It is from this equation that we derive the well-known fact that there exists an approximately 26 percent chance of at least one 1-percent-annual-chance flood during a 30-year mortgage. That fact applies only to stationary conditions, but $P(x)$ may also be a function of time. Consider the effect of SLR on flood hazard at Grand Isle, LA, where RSL change has averaged almost 1 cm/yr since the 1950s (Figure B2):

[19] The method is easily extended to the probability of any number of floods, if desired. Similarly, the flood occurrence rate need not be defined using years, though this is by far the most common time block used in practice.

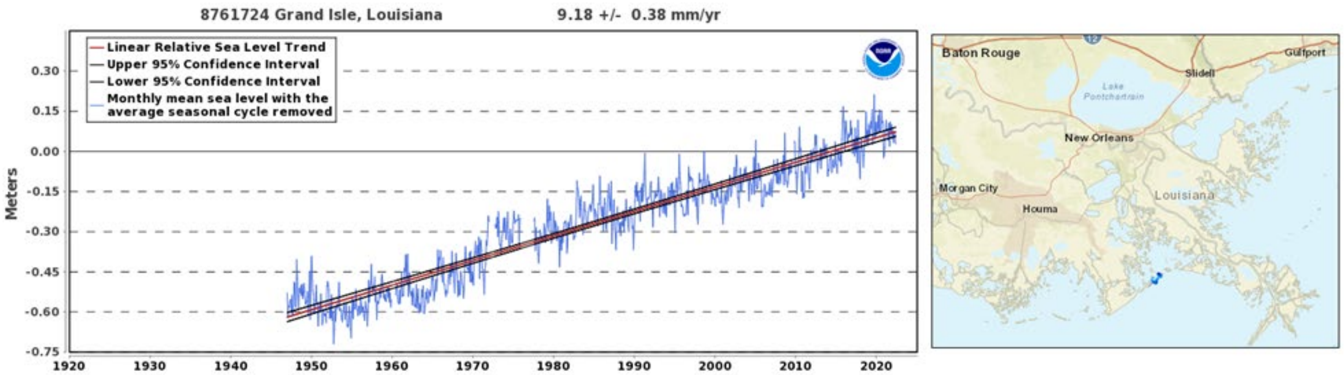


*Figure 14. Observed RSL change at Grand Isle, LA (map at right)*

At this location the 1-percent AEP total water level[20] is 6.93 feet (2.09 m) above MSL based on observations from 1947-present. As the mean sea level rises, this water level does as well. To illustrate this concept further, if we assume that this extreme water level will maintain the same relative offset of 6.93 ft from the USACE High MSL Scenario in the future, we can use equation (2) in Engineering Regulation 1100-2-8162 (USACE 2019) to project that water level into the future (in meters), beginning from the year 1992 (the midpoint of the most recent National Tidal Datum Epoch):

$$E(t) = 0.00935t + 0.000113t^2 + 2.09 \quad (2)$$

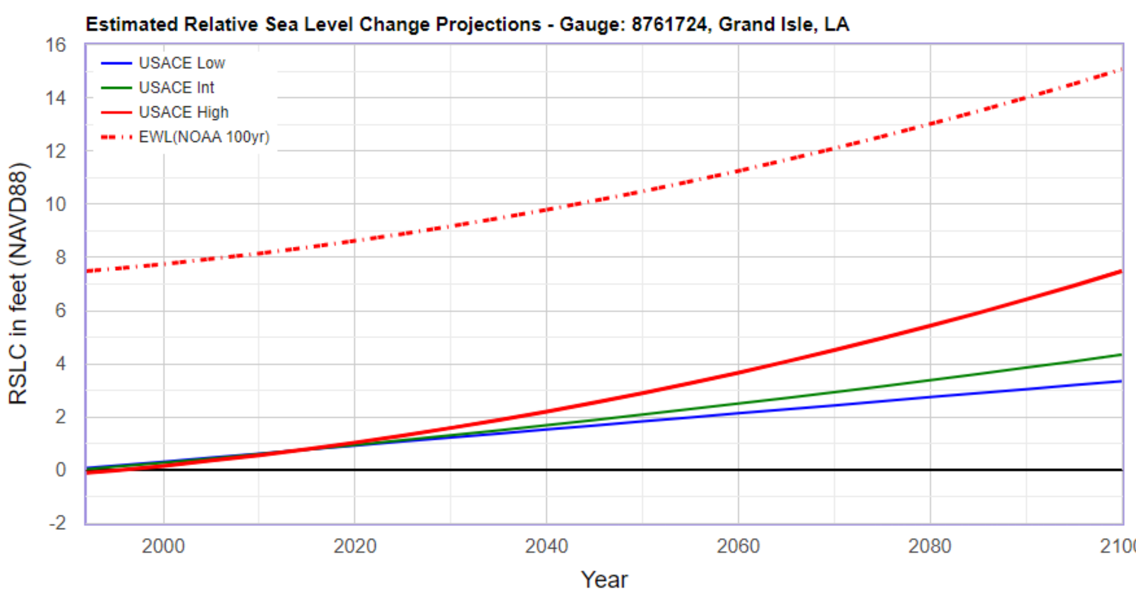


*Figure 15. The 100-year (1-percent AEP) water level as defined by NOAA, superimposed on the USACE High SLR Scenario as defined by ER 1110-2-8162*

Figures 13 and 15 depict the change over time in a flood magnitude of a given probability of exceedance per year. However, when evaluating potential projects, the change in annual flood

[20] Total water level refers to a flood height including the effects of sea level change, tides, storm surge, and waves. Exact definitions may vary depending on application, data availability, and site-specific considerations.

probability at a proposed site with a given elevation is especially important. To instead estimate the change in annual flood hazard for a fixed water level over time, we can solve equation (2) to determine the future year when various other water levels of defined probabilities today will equal that level, as shown in Table B1:

**Table B1.** Change in probability of 6.93 ft water level under USACE High Sea Level Scenario

| AEP (2014) | Height above MSL (2014) | Year when total water level equals 6.93 ft. |
|---|---|---|
| 0.01 | 6.93 | 1992 |
| 0.02 | 5.76 | 2020 |
| 0.05 | 4.49 | 2041 |
| 0.1 | 3.71 | 2052 |
| 0.2 | 3.03 | 2061 |

Table B1 shows that an extreme water level of 6.93 ft had just a 1-percent chance of occurring in 2014 but will have a 10-percent chance of occurring in 2052 and a 20-percent chance of occurring in 2061.

The above relationship between time and the annual exceedance probability of a 6.93-foot water level may be suitably estimated (root mean squared error: 1.6-percent AEP) with an exponential function:

$$AEP\ (\%) = 0.007e^{0.049t} \tag{3}$$

Where $t$ is the number of years since 1992. We can now use equation (3) to estimate $P(x)$ for this water level for any year and use equation (1) to derive the cumulative risk of experiencing at least one such water level over any period of interest. This is implemented in Table B2 and Figure 16 below:

**Table B2.** Cumulative probability of at least one 6.9-foot flood at Grand Isle over 30 years, comparing exponentially increasing risk according to USACE High Sea Level Scenario to stationary exceedance probability of 1.87-percent per year.

| Year | **Nonstationary Exponential**<br>**Initial AEP: 1.00%**<br>Annual % chance | **Nonstationary Exponential**<br>**Initial AEP: 1.00%**<br>Cum. % of >=1 event | **Stationary Equivalent over 30 Years**<br>**Annual Risk: 1.87%**<br>Annual % chance | **Stationary Equivalent over 30 Years**<br>**Annual Risk: 1.87%**<br>Cum. % of >=1 event |
|---|---|---|---|---|
| 1 | 1.00% | 1.00% | 1.87% | 1.87% |
| 2 | 1.03% | 2.02% | 1.87% | 3.70% |
| 3 | 1.07% | 3.07% | 1.87% | 5.49% |
| 4 | 1.11% | 4.15% | 1.87% | 7.26% |
| 5 | 1.15% | 5.25% | 1.87% | 8.99% |
| 6 | 1.20% | 6.39% | 1.87% | 10.69% |
| 7 | 1.24% | 7.55% | 1.87% | 12.35% |
| 8 | 1.29% | 8.74% | 1.87% | 13.99% |
| 9 | 1.34% | 9.96% | 1.87% | 15.59% |
| 10 | 1.39% | 11.21% | 1.87% | 17.17% |
| 11 | 1.45% | 12.50% | 1.87% | 18.72% |
| 12 | 1.51% | 13.82% | 1.87% | 20.23% |
| 13 | 1.57% | 15.17% | 1.87% | 21.72% |
| 14 | 1.63% | 16.55% | 1.87% | 23.18% |
| 15 | 1.70% | 17.97% | 1.87% | 24.61% |
| 16 | 1.77% | 19.42% | 1.87% | 26.02% |
| 17 | 1.84% | 20.90% | 1.87% | 27.40% |
| 18 | 1.92% | 22.42% | 1.87% | 28.76% |
| 19 | 2.00% | 23.97% | 1.87% | 30.09% |
| 20 | 2.09% | 25.56% | 1.87% | 31.39% |
| 21 | 2.18% | 27.18% | 1.87% | 32.67% |
| 22 | 2.27% | 28.83% | 1.87% | 33.93% |
| 23 | 2.37% | 30.52% | 1.87% | 35.16% |
| 24 | 2.47% | 32.54% | 1.87% | 36.37% |
| 25 | 2.58% | 33.99% | 1.87% | 37.56% |
| 26 | 2.70% | 35.77% | 1.87% | 38.72% |
| 27 | 2.82% | 37.58% | 1.87% | 39.87% |
| 28 | 2.94% | 39.42% | 1.87% | 40.99% |
| 29 | 3.08% | 41.28% | 1.87% | 42.09% |
| 30 | 3.22% | 43.17% | 1.87% | 43.17% |

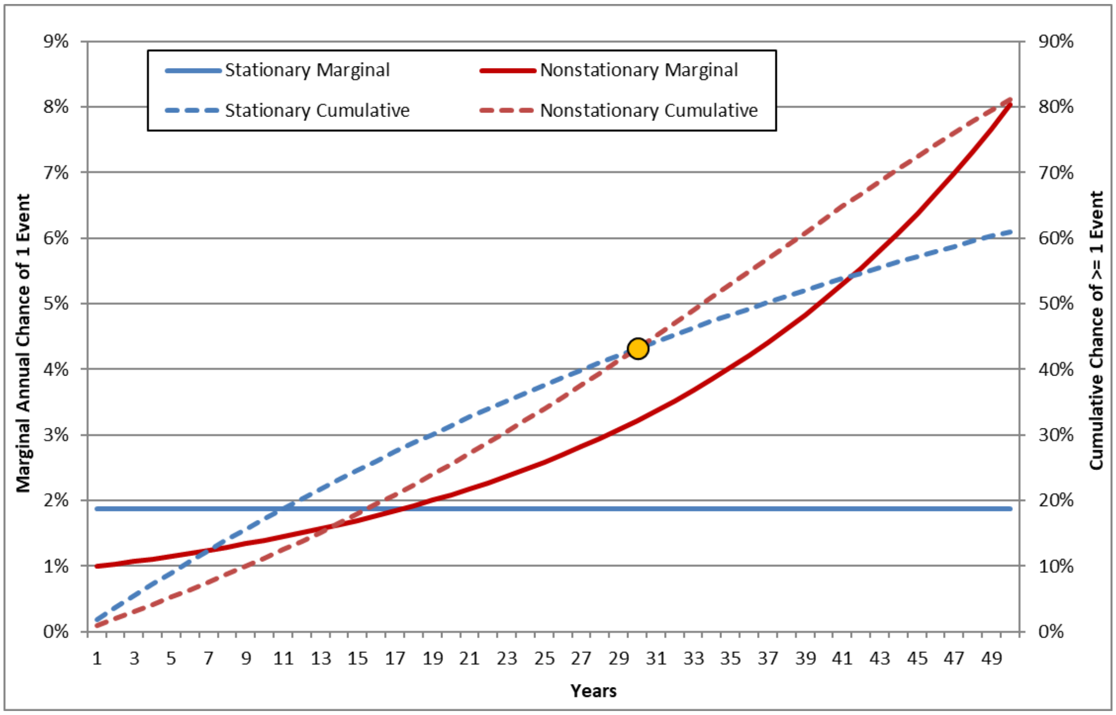


*Figure 16. Cumulative probability of at least one 6.9-foot flood at Grand Isle, LA*

As shown in the table and figure above, the cumulative probability of at least one flood with a height of 6.9 feet at Grand Isle in 30 years is 43.17 percent, which is equal to the probability which would result from an annual exceedance probability of 1.87 percent every year under stationary conditions. This finding provides a more concise way to communicate cumulative risk to a lay audience than attempting to explain all the steps and equations above: "your risk of experiencing this flood over this period is the same as if the chances were an unchanging 1.87 percent per year." It might also serve for estimating flood benefits under some simplifying assumptions.

Table B2 also allows us to answer the question posed at the beginning of this section: what is the best representation of the elevation of the CISA floodplain with a 1-percent AEP for Grand Isle, where the influence of climate change on global sea levels and of various geologic processes on land movement is causing water levels to rise rapidly over time? At the present time, the 1-percent AEP water level is 6.93 feet. At the end of 30 years, we may project it to be 8.32 feet (using the relationship between AEP and water level shown in Table B1, combined with a projection that the probability of a 6.93-foot flood will increase to 3.22 percent assuming that the offset between the two floods will remain a constant 1.4 feet as shown in Table B2). For a floodplain representation that integrates this change over time, we can similarly estimate 7.7 feet with the same arithmetic. These three levels would correspond to the gray, green, and red lines, respectively, in Figure B1. For an example of time-varying, risk-based infrastructure design (as opposed to floodplain mapping) the user is referred to section 4.2 of Sweet et al. (2022). (See Read and Vogel (2015), Yan et al. (2017), and Jiang et al. (2019) for more background information on methods for characterizing changes in flood hazards over a fixed future period.)

Several important caveats must be kept in mind when considering this approach. The most important is that while the math underlying this approach is relatively straightforward, the entire exercise relies upon a single projection of changing future flood probability. Sea level change provides a situation where such projections may be made based on relatively simple empirical functions developed by the scientific community using actionable science from oceanography, glaciology, and other fields, but significant uncertainty in both future emissions and the oceanographic response thereto necessitate using multiple scenarios to cover the range of reasonably plausible future conditions.

We have elected to demonstrate this alternative interpretation of the integration of current and future climate conditions under a single future scenario using a near-term SLR example, since there are narrower bands of uncertainty on the range of plausible SLR during this period (Sweet et al. 2022). In contrast, the wide range of future precipitation scenarios in established GCM ensembles (e.g., CMIP6) combined with challenges of modeling hydrologic extremes makes future riverine flood hazards more difficult to predict. However, this method could be extended to incorporate confidence intervals that depict the uncertainty of a single projection or even the uncertainty across an ensemble of projections arising from different GCMs. In many cases, the elevation of a CISA floodplain may be more sensitive to the range of uncertainty across a set of climate scenarios defined by different combinations of emissions trajectories and GCM models than it may be to the choice of method for integrating current and future climate conditions over a single scenario.

Another key assumption used in this alternative integration approach is the stationarity of extremes relative to the mean, allowing floods to be estimated with offsets between water levels of given probabilities without considering how those offsets might change over time. This can be resolved with hydrodynamic modeling of projected changes in storm climatology (Gori et al. 2022), but with a corresponding increase in both computational and human expense. Finally, if these probabilities are to be used for computing risks to value infrastructure or financial instruments, it becomes important to consider how the value of assets at risk may also change over time, and how future rates of inflation may affect the time value of money. Because projections are path-dependent, high average accuracy of relative changes may not imply accurate values of future risk. In the end, no projection will provide an exact forecast, but they may still have value for risk-informed planning.

## Publication Bibliography

Alfieri, Lorenzo; Feyen, Luc; Di Baldassarre, Giuliano (2016): Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies. In *Climatic Change* 136 (3-4), pp. 507–521. DOI: 10.1007/s10584-016-1641-1.

American Association of State Highway and Transportation Officials (2014): AASHTO Drainage Manual. First edition. Washington, D.C.: American Association of State Highway and Transportation Officials.

American Association of State Highway and Transportation Officials (2020): LRFD Bridge Design Specifications. 9th edition. Washington, DC: American Association of State Highway and Transportation Officials.

American Meteorological Society (2020): A National Extreme Storm Database for Infrastructure Assessments. With assistance of John England, George Hayes, Charles McWilliams, Brian Mulcahy, Tye Parzybok, Melissa Mika. 34th Conference on Hydrology Extreme Rainfall and Hydrologic Extremes. Boston, MA, January 14, 2020. Available online at https://ams.confex.com/ams/2020Annual/meetingapp.cgi/Paper/365461.

ASFPM Riverine Erosion Hazards Working Group (2016): ASFPM Riverine Erosion Hazards White Paper. Association of State Floodplain Managers. Available online at https://asfpm-library.s3-us-west-2.amazonaws.com/ASFPM_Pubs/ASFPM_Riverine_Erosion_White_Paper_2016.pdf.

Association of State Floodplain Managers Foundation (2019): Urban Flooding - Moving Towards Resilience. A Summary Report Based on the 6th Assembly of the Gilbert F. White National Flood Policy Forum. Association of State Floodplain Managers Foundation. Washington, D. C. Available online at https://www.asfpmfoundation.org/ace-images/UrbanFloodingReport.pdf.

Awasthi, C.; Archfield, S. A.; Ryberg, K. R.; Kiang, J. E.; Sankarasubramanian, A. (2022): Projecting Flood Frequency Curves Under Near-Term Climate Change. In *Water Resour. Res.* 58 (8). DOI: 10.1029/2021WR031246.

BakerAECOM (2016): Sea Level Rise Pilot Study. Future Conditions Analysis and Mapping San Francisco County, California. Available online at https://default.sfplanning.org/plans-and-programs/local_coastal_prgm/CCAMP_OPC_SLR_PilotStudy_FINAL_25Jan2016.pdf.

Barnard, Patrick L.; Erikson, Li H.; Foxgrover, Amy C.; Hart, Juliette A. Finzi; Limber, Patrick; O'Neill, Andrea C. et al. (2019): Dynamic flood modeling essential to assess the coastal impacts of climate change. In *Sci Rep* 9 (1), p. 4309. DOI: 10.1038/s41598-019-40742-z.

Barth, Nancy A.; Villarini, Gabriele; Nayak, Munir A.; White, Kathleen (2017): Mixed populations and annual flood frequency estimates in the western United States: The role of atmospheric rivers. In *Water Resour. Res.* 53 (1), pp. 257–269. DOI: 10.1002/2016WR019064.

Barth, Nancy A.; Villarini, Gabriele; White, Kathleen (2019): Accounting for mixed populations in flood frequency analysis: Bulletin 17C perspective. In *J. Hydrologic Eng.* 24(3). DOI: 10.1061/(ASCE)HE.1943-5584.0001762.

Bassiouni, Maoya; Vogel, Richard M.; Archfield, Stacey A. (2016): Panel regressions to estimate low-flow response to rainfall variability in ungaged basins. In *Water Resour. Res.* 52 (12), pp. 9470–9494. DOI: 10.1002/2016WR018718.

Batibeniz, Fulden; Ashfaq, Moetasim; Diffenbaugh, Noah S.; Key, Kesondra; Evans, Katherine J.; Turuncoglu, Ufuk Utku; Önol, Barış (2020): Doubling of U.S. Population Exposure to Climate Extremes by 2050. In *Earth's Future* 8 (4). DOI: 10.1029/2019EF001421.

Beltaos, Spyros (2021): Assessing the Frequency of Floods in Ice-Covered Rivers under a Changing Climate: Review of Methodology. In *Geosciences* 11 (12), p. 514. DOI: 10.3390/geosciences11120514.

Bender, Jens; Wahl, Thomas; Müller, Alfred; Jensen, Jürgen (2016): A multivariate design framework for river confluences. In *Hydrological Sciences Journal* 61 (3), pp. 471–482. DOI: 10.1080/02626667.2015.1052816.

Bentivoglio, Roberto; Isufi, Elvin; Jonkman, Sebastian Nicolaas; Taormina, Riccardo (2022): Deep Learning Methods for Flood Mapping: A Review of Existing Applications and Future Research Directions. In *Hydrol. Earth Syst. Sci.* 26, pp. 4345–4378, DOI: 10.5194/hess-26-4345-2022.

Bertola, Miriam; Viglione, Alberto; Vorogushyn, Sergiy; Lun, David; Merz, Bruno; Blöschl, Günter (2021): Do small and large floods have the same drivers of change? A regional attribution analysis in Europe. In *Hydrol. Earth Syst. Sci.* 25 (3), pp. 1347–1364. DOI: 10.5194/hess-25-1347-2021.

Betson, Roger P. (1964): What is watershed runoff? In *J. Geophys. Res.* 69 (8), pp. 1541–1552. DOI: 10.1029/JZ069i008p01541.

Beyene, Mussie T.; Leibowitz, Scott G.; Pennino, Michael J. (2021): Parsing Weather Variability and Wildfire Effects on the Post-Fire Changes in Daily Stream Flows: A Quantile-Based Statistical Approach and Its Application. In *Water Resour. Res.* 57 (10). DOI: 10.1029/2020WR028029.

Blazewicz, Michael; Jagt, Katie; Sholtes, Joel (2020): Colorado Fluvial Hazard Zone Delineation Protocol v1.0: Unpublished.

Bloemen, Pieter; Reeder, Tim; Zevenbergen, Chris; Rijke, Jeroen; Kingsborough, Ashley (2018): Lessons learned from applying adaptation pathways in flood risk management and challenges for the further development of this approach. In *Mitigation and adaptation strategies for global change* 23 (7), pp. 1083–1108. DOI: 10.1007/s11027-017-9773-9.

Blöschl, Günter (2022): Three hypotheses on changing river flood hazards. In *Hydrol. Earth Syst. Sci.* 26 (19), pp. 5015-5033. DOI: 10.5194/hess-26-5015-2022

Blum, Annalise G.; Ferraro, Paul J.; Archfield, Stacey A.; Ryberg, Karen R. (2020): Causal Effect of Impervious Cover on Annual Flood Magnitude for the United States. In *Geophys. Res. Lett.* 47 (5). DOI: 10.1029/2019GL086480.

Brogan, Daniel J.; Nelson, Peter A.; MacDonald, Lee H. (2017): Reconstructing extreme post-wildfire floods: a comparison of convective and mesoscale events. In *Earth Surf. Process. Landforms* 42 (15), pp. 2505–2522. DOI: 10.1002/esp.4194.

Brown, Casey; Ghile, Yonas; Laverty, Mikaela; Li, Ke (2012): Decision scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector. In *Water Resour. Res.* 48 (9). DOI: 10.1029/2011WR011212.

Brunner, Manuela I.; Melsen, Lieke A.; Newman, Andrew J.; Wood, Andrew W.; Clark, Martyn P. (2020): Future streamflow regime changes in the United States: assessment using functional classification. In *Hydrol. Earth Syst. Sci.* 24 (8), pp. 3951–3966. DOI: 10.5194/hess-24-3951-2020.

Brunner, Manuela I.; Swain, Daniel L.; Wood, Raul R.; Willkofer, Florian; Done, James M.; Gilleland, Eric; Ludwig, Ralf (2021): An extremeness threshold determines the regional response of floods to changes in rainfall extremes. In *Commun Earth Environ* 2 (1). DOI: 10.1038/s43247-021-00248-x.

Buffin-Bélanger, Thomas; Biron, Pascale M.; Larocque, Marie; Demers, Sylvio; Olsen, Taylor; Choné, Guénolé et al. (2015): Freedom space for rivers: An economically viable river management concept in a changing climate. In *Geomorphology* 251, pp. 137–148. DOI: 10.1016/j.geomorph.2015.05.013.

Bull, W. B. (1991): Geomorphic responses to climatic change. New York, NY (United States): Oxford University Press. Available online at https://www.osti.gov/biblio/5603696.

Bureau of Public Roads (1954): Policy on Interstate System Projects (Policy and Procedure Memorandum (PPM), No. 20-4).

Burke Engineering (2018): Indiana Fluvial Erosion Hazard Mitigation Manual. Available online at https://feh.iupui.edu/wp-content/uploads/2019/03/Indiana-Fluvial-Erosion-Hazard-Mitigation-Manual-FINAL.pdf.

Burn, Donald H. (1990): Evaluation of regional flood frequency analysis with a region of influence approach. In *Water Resour. Res.* 26 (10), pp. 2257–2265. DOI: 10.1029/WR026i010p02257.

Burrell, B. C.; Beltaos, S.; Turcotte, B. (2022): Effects of climate change on river-ice processes and ice jams. In *International Journal of River Basin Management*, pp. 1–21. DOI: 10.1080/15715124.2021.2007936.

Callaghan, David Patrick; Hughes, Michael G. (2022): Assessing flood hazard changes using climate model forcing: Nat. Hazards Earth Syst. Sci. Available online at https://nhess.copernicus.org/articles/22/2459/2022/.

Candel, Jasper H. J.; Kleinhans, Maarten G.; Makaske, Bart; Hoek, Wim Z.; Quik, Cindy; Wallinga, Jakob (2018): Late Holocene channel pattern change from laterally stable to meandering – a palaeohydrological reconstruction. In *Earth Surf. Dynam.* 6 (3), pp. 723–741. DOI: 10.5194/esurf-6-723-2018.

Carr, Meredith L.; Vuyovich, Carrie M. (2014): Investigating the effects of long-term hydro-climatic trends on Midwest ice jam events. In *Cold Regions Science and Technology* 106-107, pp. 66–81. DOI: 10.1016/j.coldregions.2014.06.003.

Coelho, Gustavo de A.; Ferreira, Celso M.; Johnston, Jeremy; Kinter, James L.; Dollan, Ishrat J.; Maggioni, Viviana (2022): Potential Impacts of Future Extreme Precipitation Changes on Flood Engineering Design Across the Contiguous United States. In *Water Resour. Res.* 58 (4). DOI: 10.1029/2021WR031432.

Cohn, Timothy A.; Lins, Harry F. (2005): Nature's style: Naturally trendy. In *Geophys. Res. Lett.* 32 (23). DOI: 10.1029/2005GL024476.

Collins, M. J.; Hodgkins, G. A.; Archfield, S. A.; Hirsch, R. M. (2022): The Occurrence of Large Floods in the United States in the Modern Hydroclimate Regime: Seasonality, Trends, and Large-Scale Climate Associations. In *Water Resour. Res.* 58 (2). DOI: 10.1029/2021WR030480.

Costa, John E.; O'Connor, Jim E. (1995): Geomorphically effective floods. In : Geophysical Monograph Series. Washington, D. C.: American Geophysical Union, pp. 45–56. DOI: 10.1029/GM089p0045.

Crowell, Mark; Honeycutt, Maria; Hatheway, Darryl (1999): Coastal erosion hazards study: phase one mapping. In *Journal of Coastal Research*, pp. 10–20. Available online at https://www.jstor.org/stable/25736180.

Davenport, Frances V.; Herrera-Estrada, Julio E.; Burke, Marshall; Diffenbaugh, Noah S. (2020): Flood Size Increases Nonlinearly Across the Western United States in Response to Lower Snow-Precipitation Ratios. In *Water Resour. Res.* 56 (1). DOI: 10.1029/2019WR025571.

Debbage, Neil; Shepherd, J. M. (2018): The Influence of Urban Development Patterns on Streamflow Characteristics in the Charlanta Megaregion. In *Water Resour. Res.* 54 (5), pp. 3728–3747. DOI: 10.1029/2017WR021594.

Dessai, Suraje; Hulme, Mike (2004): Does climate adaptation policy need probabilities? In *Climate Policy* 4 (2), pp. 107–128. DOI: 10.1080/14693062.2004.9685515.

Dethier, Evan N.; Sartain, Shannon L.; Renshaw, Carl E.; Magilligan, Francis J. (2020): Spatially coherent regional changes in seasonal extreme streamflow events in the United States and Canada since 1950. In *Science Advances* 6 (49). DOI: 10.1126/sciadv.aba5939.

Dickinson, Jesse E.; Harden, Tessa M.; McCabe, Gregory J. (2019): Seasonality of climatic drivers of flood variability in the conterminous United States. In *Sci Rep* 9 (1), p. 15321. DOI: 10.1038/s41598-019-51722-8.

Dirección de Adaptación al Cambio Climático y Gestión Estratégica del Riesgo (2014): LINEAMIENTOS BÁSICOS DE ADAPTACIÓN AL CAMBIO CLIMÁTICO EN EL DISEÑO DE PUENTES EN EL SALVADOR. Second. Ministerio de Obras Públicas, Transporte, Vivienda y Desarrollo Urbano de El Salvador. El Salvador.

Dullo, Tigstu T.; Darkwah, George K.; Gangrade, Sudershan; Morales-Hernández, Mario; Sharif, M. Bulbul; Kalyanapu, Alfred J. et al. (2021): Assessing climate-change-induced flood risk in the Conasauga River watershed: an application of ensemble hydrodynamic inundation modeling. In *Nat. Hazards Earth Syst. Sci.* 21 (6), pp. 1739–1757. DOI: 10.5194/nhess-21-1739-2021.

Dunne, Thomas; Moore, T.; Taylor, C. H. (1975): Recognition and prediction of runoff-producing zones in humid regions. In *Hydrol. Sci. Bull* 20 (3), pp. 305–327. Available online at https://sites.google.com/a/hydrogeomorphology.com/home/publications/1970s_publication/09_recognition_and_prediction_of_runoff_producing_zones_in_humid_regions_1975.pdf.

Dust, David; Wohl, Ellen (2012): Conceptual model for complex river responses using an expanded Lane's relation. In *Geomorphology* 139-140, pp. 109–121. DOI: 10.1016/j.geomorph.2011.10.008.

Elko, Nicole; Feddersen, Falk; Foster, Diane; Hapke, Cheryl; McNinch, Jesse; Mulligan, Ryan et al. (2015): The future of nearshore processes research. In *Shore & Beach* 83 (1), pp. 13–38. Available online at https://asbpa.org/wp-content/uploads/2016/03/nearshorefuturespring2015_83_1-2.pdf.

England, John F.; Cohn, Timothy A.; Faber, Beth A.; Stedinger, Jery R.; Thomas, Wilbert O.; Veilleux, Andrea G. et al. (2019): Guidelines for determining flood flow frequency — Bulletin 17C: Techniques and Methods. Available online at https://doi.org/10.3133/tm4B5.

England, John F.; Julien, Pierre Y.; Velleux, Mark L. (2014): Physically-based extreme flood frequency with stochastic storm transposition and paleoflood data on large watersheds. In *Journal of Hydrology* 510, pp. 228–245. DOI: 10.1016/j.jhydrol.2013.12.021.

Enwright, Nicholas M.; Wang, Lei; Dalyander, P. Soupy; Wang, Hongqing; Osland, Michael J.; Mickey, Rangley C. et al. (2021): Assessing Habitat Change and Migration of Barrier Islands. In *Estuaries and Coasts* 44 (8), pp. 2073–2086. DOI: 10.1007/s12237-021-00971-w.

Executive Office of the President (1977): Executive Order 11988 - Floodplain management, EO 11988. Source: 42 FR 26951, 3 CFR, 1977. In : Federal Register. Available online at https://www.archives.gov/federal-register/codification/executive-order/11988.html.

Executive Office of the President (2015): Executive Order 13690 – Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input, (EO) 13690. In: Federal Register. Available online at https://obamawhitehouse.archives.gov/the-press-office/2015/01/30/executive-order-establishing-federal-flood-risk-management-standard-and-.

Farmer, William H.; Vogel, Richard M. (2016): On the deterministic and stochastic use of hydrologic models. In *Water Resour. Res.* 52 (7), pp. 5619–5633. DOI: 10.1002/2016WR019129.

Faunt, Claudia C.; Sneed, Michelle; Traum, Jon; Brandt, Justin T. (2016): Water availability and land subsidence in the Central Valley, California, USA. In *Hydrogeol J* 24 (3), pp. 675–684. DOI: 10.1007/s10040-015-1339-x.

Federal Interagency Floodplain Management Task Force (FIFM-TF) (1988): Further Advice on Executive Order 11988 Floodplain Management. Available online at https://www.gsa.gov/cdnstatic/Advice_EO11988.pdf.

Federal National Climate Assessment and Development Advisory Committee (2014): Climate Change Impacts in the United States. Third U.S. National Climate Assessment. Washington, DC: U.S. Global Change Research Program. Available online at https://www.globalchange.gov/browse/reports/climate-change-impacts-united-states-third-national-climate-assessment-0.

FEMA (n.d.): FEMA Region I Coastal Erosion Hazard Map. FEMA. Available online at https://www.arcgis.com/apps/webappviewer/index.html?id=a4aa86031a3a40be9d453d781ff210b3.

FEMA (1999): Riverine erosion hazard areas. Mapping feasibility study. FEMA. Washington, D. C. Available online at https://asfpm-library.s3-us-west-2.amazonaws.com/General/FEMA_riverine_erosion_hazard_area_1999.pdf, checked on 7/27/2020.

FEMA (2018): Guidance for Flood Risk Analysis and Mapping. Ice-Jam Analyses and Mapping. Available online at https://www.fema.gov/sites/default/files/2020-02/Ice_Jam_Guidance_Feb_2018.pdf.

FEMA (2021a): Guidelines and Standards for Flood Risk Analysis and Mapping Activities Under the Risk MAP Program. FEMA. Available online at https://www.fema.gov/flood-maps/guidance-reports/guidelines-standards.

FEMA (2021b): Coastal Numerical Models Meeting the Minimum Requirement of the National Flood Insurance Program. FEMA. Available online at https://www.fema.gov/flood-maps/products-tools/numerical-models/coastal, updated on 12/23/2021.

FEMA (2022a): Numerical Models Meeting the Minimum Requirements of the National Flood Insurance Program. FEMA. Available online at https://www.fema.gov/flood-maps/products-tools/numerical-models, updated on 1/7/2022.

FEMA (2022b): Guidance for FEMA's Risk Mapping, Assessment and Planning. FEMA. Available online at https://www.fema.gov/flood-maps/guidance-reports/guidelines-standards/guidance-femas-risk-mapping-assessment-and-planning, updated on 5/4/2022.

FHWA (2020): Climate Data Processing Tool 2.1. US Department of Transportation. Available online at https://fhwaapps.fhwa.dot.gov/cmip, updated on 2020.

First Street Foundation (n.d.): Risk Factor. First Street Foundation. Available online at https://riskfactor.com/, updated on 2022.

Floyd, Ian E.; Ramos-Villanueva, Marielys; Heath, Ronald E.; Brown, Stephen (2019): Evaluating Post-Wildfire Impacts to Flood Risk Management (FRM): Las Conchas Wildfire – New Mexico. USACE (U.S. Army Corps of Engineers (USACE) Regional Sediment Management Technical Note (RSM-TN)). Available online at https://erdc-library.erdc.dren.mil/jspui/bitstream/11681/32910/3/ERDC-TN%20RSM-19-4.pdf.

Foltz, Randy B.; Robichaud, Peter R.; Rhee, Hakjun (2008): A synthesis of postfire road treatments for BAER teams: methods, treatment effectiveness, and decisionmaking tools for rehabilitation. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Available online at https://doi.org/10.2737/RMRS-GTR-228.

Ford, Chanse M.; Kendall, Anthony D.; Hyndman, David W. (2021): Snowpacks decrease and streamflows shift across the eastern US as winters warm. In *The Science of the total environment* 793, p. 148483. DOI: 10.1016/j.scitotenv.2021.148483.

François, B.; Schlef, K. E.; Wi, S.; Brown, C. M. (2019): Design considerations for riverine floods in a changing climate – A review. In *Journal of Hydrology* 574, pp. 557–573. DOI: 10.1016/j.jhydrol.2019.04.068.

Frans, Chris; Istanbulluoglu, Erkan; Mishra, Vimal; Munoz-Arriola, Francisco; Lettenmaier, Dennis P. (2013): Are climatic or land cover changes the dominant cause of runoff trends in the Upper Mississippi River Basin? In *Geophys. Res. Lett.* 40 (6), pp. 1104–1110. DOI: 10.1002/grl.50262.

Gartner, John D.; Dade, William B.; Renshaw, Carl E.; Magilligan, Francis J.; Buraas, Eirik M. (2015): Gradients in stream power influence lateral and downstream sediment flux in floods. In *Geology* 43 (11), pp. 983–986. DOI: 10.1130/G36969.1.

Gartner, John D.; Hatch, Christine E.; Vogel, Eve (2019): The River Process Corridor: A Modular River Assessment Method Based on Process Units and Widely Available Data in the Northeast US: Water Reports. Available online at https://scholarworks.umass.edu/water_reports/6/.

Gilroy, Kristin L.; McCuen, Richard H. (2012): A nonstationary flood frequency analysis method to adjust for future climate change and urbanization. In *Journal of Hydrology* 414-415, pp. 40–48. DOI: 10.1016/j.jhydrol.2011.10.009.

Giuntoli, Ignazio; Prosdocimi, Ilaria; Hannah, David M. (2021): Going Beyond the Ensemble Mean: Assessment of Future Floods From Global Multi-Models. In *Water Resour. Res.* 57 (3). DOI: 10.1029/2020WR027897.

Gori, Avantika; Lin, Ning; Xi, Dazhi; Emanuel, Kerry (2022): Tropical cyclone climatology change greatly exacerbates US extreme rainfall–surge hazard. In *Nat. Clim. Chang.* 12 (2), pp. 171–178. DOI: 10.1038/s41558-021-01272-7.

Griffin, Adam; Kay, Alison; Stewart, Lisa; Spencer, Peter (2022): Climate change allowances, non-stationarity and flood frequency analyses. In *J Flood Risk Management*. DOI: 10.1111/jfr3.12783.

Gutierrez, Benjamin T.; Plant, Nathaniel G.; Thieler, E. Robert (2011): A Bayesian network to predict coastal vulnerability to sea level rise. In *J. Geophys. Res.* 116 (F2). DOI: 10.1029/2010JF001891.

Haasnoot, Marjolijn; Kwakkel, Jan H.; Walker, Warren E.; Maat, Judith ter (2013): Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. In *Global Environmental Change* 23 (2), pp. 485–498. DOI: 10.1016/j.gloenvcha.2012.12.006.

Haberlandt, U.; Radtke, I. (2014): Hydrological model calibration for derived flood frequency analysis using stochastic rainfall and probability distributions of peak flows. In *Hydrol. Earth Syst. Sci.* 18 (1), pp. 353–365. DOI: 10.5194/hess-18-353-2014.

Haddeland, Ingjerd; Matheussen, Bernt V.; Lettenmaier, Dennis P. (2002): Influence of spatial resolution on simulated streamflow in a macroscale hydrologic model. In *Water Resour. Res.* 38 (7), 29-1-29-10. DOI: 10.1029/2001WR000854.

Hall, Jim W.; Harvey, Hamish; Manning, Lucy J. (2019): Adaptation thresholds and pathways for tidal flood risk management in London. In *Climate Risk Management* 24, pp. 42–58. DOI: 10.1016/j.crm.2019.04.001.

Hallegatte, Stéphane; Shah, Ankur; Lempert, Robert; Brown, Casey; Gill, Stuart (2012): Investment Decision Making Under Deep Uncertainty: Application to Climate Change. World Bank. Washington, DC (Policy Research Working Paper, 6193). Available online at https://openknowledge.worldbank.org/handle/10986/12028.

Harrison, Stephan; Kargel, Jeffrey S.; Huggel, Christian; Reynolds, John; Shugar, Dan H.; Betts, Richard A. et al. (2018): Climate change and the global pattern of moraine-dammed glacial lake outburst floods. In *The Cryosphere* 12 (4), pp. 1195–1209. DOI: 10.5194/tc-12-1195-2018.

Hecht, Jory S.; Barth, Nancy A.; Ryberg, Karen R.; Gregory, Angela E. (2022): Simulation experiments comparing nonstationary design-flood adjustments based on observed annual peak flows in the conterminous United States. In *J. of Hydrology X*. DOI:10.1016/j.hydroa.2021.100115.

Hecht, Jory S.; Kirshen, Paul H. (2019): Minimizing Urban Floodplain Management Regrets under Deeply Uncertain Climate Change. In *J. Water Resour. Plann. Manage.* 145 (2), p. 4018096. DOI: 10.1061/(ASCE)WR.1943-5452.0001012.

Hecht, Jory S.; Vogel, Richard M. (2020): Updating urban design floods for changes in central tendency and variability using regression. In *Advances in Water Resources* 136, p. 103484. DOI: 10.1016/j.advwatres.2019.103484.

Hecht, Jory S.; Zia, Asim; Clemins, Patrick J.; Schroth, Andrew W.; Winter, Jonathan M.; Oikonomou, Panagiotis D.; Rizzo, Donna M. (2022): Modeling the sensitivity of cyanobacteria blooms to plausible changes in precipitation and air temperature variability. In *The Sci. Tot. Environ.* 812, p. 151586. DOI: 10.1016/j.scitotenv.2021.151586.

Her, Younggu; Yoo, Seung-Hwan; Cho, Jaepil; Hwang, Syewoon; Jeong, Jaehak; Seong, Chounghyun (2019): Uncertainty in hydrological analysis of climate change: multi-parameter vs. multi-GCM ensemble predictions. In *Sci Rep* 9 (1), p. 4974. DOI: 10.1038/s41598-019-41334-7.

Herman, Jonathan D.; Reed, Patrick M.; Zeff, Harrison B.; Characklis, Gregory W. (2015): How Should Robustness Be Defined for Water Systems Planning under Change? In *J. Water Resour. Plann. Manage.* 141 (10), p. 4015012. DOI: 10.1061/(ASCE)WR.1943-5452.0000509.

Hirsch, Robert M.; Archfield, Stacey A. (2015): Not higher but more often. In *Nat. Clim. Chang.* 5 (3), pp. 198–199. DOI: 10.1038/nclimate2551.

Hirschboeck, Katherine K. (1987): Hydroclimatically-defined mixed distributions in partial duration flood series. In *Hydrologic frequency modeling*, pp. 199–212. Available online at https://kkh.ltrr.arizona.edu/kkh/pdfs/Hydro-Mixed-Distr-1987-kkh-ocr.pdf.

Hodgkins, G. A.; Dudley, R. W.; Archfield, S. A.; Renard, B. (2019): Effects of climate, regulation, and urbanization on historical flood trends in the United States. In *Journal of Hydrology* 573, pp. 697–709. DOI: 10.1016/j.jhydrol.2019.03.102.

Hodgkins, Glenn A.; Whitfield, Paul H.; Burn, Donald H.; Hannaford, Jamie; Renard, Benjamin; Stahl, Kerstin et al. (2017): Climate-driven variability in the occurrence of major floods across North America and Europe. In *Journal of Hydrology* 552, pp. 704–717. DOI: 10.1016/j.jhydrol.2017.07.027.

Hollis, G. E. (1975): The effect of urbanization on floods of different recurrence interval. In *Water Resour. Res.* 11 (3), pp. 431–435. DOI: 10.1029/WR011i003p00431.

Hosking, J. R. M.; Wallis, James R. (2009): Regional Frequency Analysis. An Approach Based on L-moments: Cambridge University Press. Available online at https://doi.org/10.1017/CBO9780511529443.

Huang, Huanping; Patricola, Christina M.; Winter, Jonathan M.; Osterberg, Erich C.; Mankin, Justin S. (2021): Rise in Northeast US extreme precipitation caused by Atlantic variability and climate change. In *Weather and Climate Extremes* 33, p. 100351. DOI: 10.1016/j.wace.2021.100351.

Huang, Huilin; Fischella, Michael R.; Liu, Yufei; Ban, Zhaoxin; Fayne, Jessica V.; Li, Dongyue et al. (2022): Changes in Mechanisms and Characteristics of Western U.S. Floods Over the Last Sixty Years. In *Geophys. Res. Lett.* 49 (3). DOI: 10.1029/2021GL097022.

Huang, Xingying; Swain, Daniel L. (2022): Climate change is increasing the risk of a California megaflood. In *Science advances* 8 (32), eabq0995. DOI: 10.1126/sciadv.abq0995.

Huang, Yingchun; Bárdossy, András; Zhang, Ke (2019): Sensitivity of hydrological models to temporal and spatial resolutions of rainfall data. In *Hydrol. Earth Syst. Sci.* 23 (6), pp. 2647–2663. DOI: 10.5194/hess-23-2647-2019.

Ivancic, Timothy J.; Shaw, Stephen B. (2015): Examining why trends in very heavy precipitation should not be mistaken for trends in very high river discharge. In *Climatic Change* 133 (4), pp. 681–693. DOI: 10.1007/s10584-015-1476-1.

Jain, Shaleen; Lall, Upmanu (2000): Magnitude and timing of annual maximum floods: Trends and large-scale climatic associations for the Blacksmith Fork River, Utah. In *Water Resour. Res.* 36 (12), pp. 3641–3651. DOI: 10.1029/2000WR900183.

Jain, Shaleen; Lall, Upmanu (2001): Floods in a changing climate: Does the past represent the future? In *Water Resour. Res.* 37 (12), pp. 3193–3205. DOI: 10.1029/2001WR000495.

Jennings, C. E.; Presnail, M.; Kurak, E.; Meier, R.; Schmidt, C.; Palazzolo, J. et al. (2016): Historical Landslide Inventory for the Twin Cities Metropolitan Area. Minnesota Department of Natural Resources. Available online at https://files.dnr.state.mn.us/waters/watermgmt_section/shoreland/landslide-inventory.pdf.

Jiang, Cong; Xiong, Lihua; Yan, Lei; Dong, Jianfan; Xu, Chong-Yu (2019): Multivariate hydrologic design methods under nonstationary conditions and application to engineering practice. In *Hydrol. Earth Syst. Sci.* 23 (3), pp. 1683–1704. DOI: 10.5194/hess-23-1683-2019.

Kao, Shih-Chieh; Chang, Ni-Bin (2012): Copula-Based Flood Frequency Analysis at Ungauged Basin Confluences: Nashville, Tennessee. In *J. Hydrol. Eng.* 17 (7), pp. 790–799. DOI: 10.1061/(ASCE)HE.1943-5584.0000477.

Kilgore, Roger; Thomas Jr, Wilbert O.; Douglass, Scott; Webb, Bret; Hayhoe, Katharine; Stoner, Anne et al. (2019): Applying Climate Change Information to Hydrologic and Coastal Design of

Transportation Infrastructure (NCHRP Project 15-61). Available online at https://trid.trb.org/view/1695370.

King, David; Schrag, Daniel; Dadi, Zhou; Ye, Qi; Ghosh, Arunabha (2015): Climate Change: A Risk Assessment. Centre for Science and Policy, University of Cambridge. Available online at https://www.csap.cam.ac.uk/media/uploads/files/1/climate-change--a-risk-assessment-v11.pdf.

Kinoshita, Alicia M.; Hogue, Terri S.; Napper, Carolyn (2014): Evaluating Pre- and Post-Fire Peak Discharge Predictions across Western U.S. Watersheds. In *J Am Water Resour Assoc* 50 (6), pp. 1540–1557. DOI: 10.1111/jawr.12226.

Kline, Michael; Cahoon, Barry (2010): Protecting River Corridors in Vermont. In *J Am Water Resour Assoc* 46 (2), pp. 227–236. DOI: 10.1111/j.1752-1688.2010.00417.x.

Kopp, Robert E.; Gilmore, Elisabeth A.; Little, Christopher M.; Lorenzo-Trueba, Jorge; Ramenzoni, Victoria C.; Sweet, William V. (2019): Usable Science for Managing the Risks of Sea-Level Rise. In *Earth's Future* 7 (12), pp. 1235–1269. DOI: 10.1029/2018EF001145.

Kundzewicz, Z. W.; Krysanova, V.; Dankers, R.; Hirabayashi, Y.; Kanae, S.; Hattermann, F. F. et al. (2016): Differences in flood hazard projections in Europe – their causes and consequences for decision making. In *Hydrological Sciences Journal*. DOI: 10.1080/02626667.2016.1241398.

Kunkel, K. E.; Easterling, D. R.; Karl, T. R.; Biard, J. C.; Champion, S. M.; Gleason, B. E. et al. (2020): Incorporation of the Effects of Future Anthropogenically Forced Climate Change in Intensity-Duration-Frequency Design Values: Final Report. North Carolina Institute for Climate, North Carolina State University. Available online at https://precipitationfrequency.ncics.org/pdfs/RC_2517_Final_Report_version2_Sep_04_2020_clean.pdf.

Lamontagne, Jonathan R.; Jasek, Martin; Smith, Jared D. (2021): Coupling physical understanding and statistical modeling to estimate ice jam flood frequency in the northern Peace-Athabasca Delta under climate change. In *Cold Regions Science and Technology* 192, p. 103383. DOI: 10.1016/j.coldregions.2021.103383.

Lane, E. W. (1955): Importance of fluvial morphology in hydraulic engineering: American Society of Civil Engineers (American Society of Civil Engineers Proceedings Separate, 81). Available online at https://agris.fao.org/agris-search/search.do?recordid=us201400000288.

Lawrence, Deborah; Hisdal, Hege (2011): Hydrological projections for floods in Norway under a future climate. NVE (978-82-410-0753-8). Available online at https://nve.brage.unit.no/nve-xmlui/handle/11250/2500939.

Lentz, Erika E.; Thieler, E. Robert; Plant, Nathaniel G.; Stippa, Sawyer R.; Horton, Radley M.; Gesch, Dean B. (2016): Evaluation of dynamic coastal response to sea-level rise modifies inundation likelihood. In *Nat. Clim. Chang.* 6 (7), pp. 696–700. DOI: 10.1038/nclimate2957.

Lentz, Erika E.; Zeigler, Sara L.; Thieler, E. Robert; Plant, Nathaniel G. (2021): Probabilistic patterns of inundation and biogeomorphic changes due to sea-level rise along the northeastern U.S. Atlantic coast. In *Landscape Ecol* 36 (1), pp. 223–241. DOI: 10.1007/s10980-020-01136-z.

Leopold, Luna Bergere (1968): Hydrology for Urban Land Planning. A Guidebook on the Hydrologic Effects of Urban Land Use: U.S. Geological Survey. Available online at https://pubs.er.usgs.gov/publication/cir554.

Li, Dongyue; Lettenmaier, Dennis P.; Margulis, Steven A.; Andreadis, Konstantinos (2019): The Role of Rain-on-Snow in Flooding Over the Conterminous United States. In *Water Resour. Res.* 55 (11), pp. 8492–8513. DOI: 10.1029/2019WR024950.

Lin, Ning; Kopp, Robert E.; Horton, Benjamin P.; Donnelly, Jeffrey P. (2016): Hurricane Sandy's flood frequency increasing from year 1800 to 2100. In *Proceedings of the National Academy of Sciences of the United States of America* 113 (43), pp. 12071–12075. DOI: 10.1073/pnas.1604386113.

López, J.; Francés, F. (2013): Non-stationary flood frequency analysis in continental Spanish rivers, using climate and reservoir indices as external covariates. In *Hydrol. Earth Syst. Sci.* 17 (8), pp. 3189–3203. DOI: 10.5194/hess-17-3189-2013.

Luke, Adam; Vrugt, Jasper A.; AghaKouchak, Amir; Matthew, Richard; Sanders, Brett F. (2017): Predicting nonstationary flood frequencies: Evidence supports an updated stationarity thesis in the U nited S tates. In *Water Resour. Res.* 53 (7), pp. 5469–5494. DOI: 10.1002/2016WR019676.

MacBroom, James G.; Schiff, Roy; Louisos, Jessica (2017): River and stream power assessment report including culvert and Bridge vulnerability analysis: Deerfield River basin, Massachusetts and Vermont. Available online at https://scholarworks.umass.edu/water_reports/4/.

Majone, Bruno; Avesani, Diego; Zulian, Patrick; Fiori, Aldo; Bellin, Alberto (2022): Analysis of high streamflow extremes in climate change studies: how do we calibrate hydrological models? In *Hydrol. Earth Syst. Sci.* 26 (14), pp. 3863–3883. DOI: 10.5194/hess-26-3863-2022.

Mallakpour, Iman; Villarini, Gabriele (2015): The changing nature of flooding across the central United States. In *Nat. Clim. Chang.* 5 (3), pp. 250–254. DOI: 10.1038/nclimate2516.

Maurer, Edwin P.; Kayser, Gretchen; Doyle, Laura; Wood, Andrew W. (2018): Adjusting Flood Peak Frequency Changes to Account for Climate Change Impacts in the Western United States. In *J. Water Resour. Plann. Manage.* 144 (3), Article 05017025. DOI: 10.1061/(ASCE)WR.1943-5452.0000903.

McMillan, Sara K.; Wilson, Henry F.; Tague, Christina L.; Hanes, Daniel M.; Inamdar, Shreeram; Karwan, Diana L. et al. (2018): Before the storm: antecedent conditions as regulators of hydrologic and biogeochemical response to extreme climate events. In *Biogeochemistry* 141 (3), pp. 487–501. DOI: 10.1007/s10533-018-0482-6.

McPhail, C.; Maier, H. R.; Kwakkel, J. H.; Giuliani, M.; Castelletti, A.; Westra, S. (2018): Robustness Metrics: How Are They Calculated, When Should They Be Used and Why Do They Give Different Results? In *Earth's Future* 6 (2), pp. 169–191. DOI: 10.1002/2017EF000649.

Merz, B.; Vorogushyn, S.; Uhlemann, S.; Delgado, J.; Hundecha, Y. (2012): HESS Opinions "More efforts and scientific rigour are needed to attribute trends in flood time series". In *Hydrol. Earth Syst. Sci.* 16 (5), pp. 1379–1387. DOI: 10.5194/hess-16-1379-2012.

Mickey, Rangley C.; Godsey, Elizabeth; Dalyander, P. Soupy; Gonzalez, Victor; Jenkins, Robert L.; Long, Joseph W. et al. (2020): Application of decadal modeling approach to forecast barrier island evolution. Available online at https://pubs.usgs.gov/of/2020/1001/ofr20201001.pdf.

Milly, P. C. D.; Betancourt, Julio; Falkenmark, Malin; Hirsch, Robert M.; Kundzewicz, Zbigniew W.; Lettenmaier, Dennis P.; Stouffer, Ronald J. (2008): Climate change. Stationarity is dead: whither water management? In *Science (New York, N.Y.)* 319 (5863), pp. 573–574. DOI: 10.1126/science.1151915.

Mishra, Ashok; Mukherjee, Sourav; Merz, Bruno; Singh, Vijay P.; Wright, Daniel B.; Villarini, Gabriele et al. (2022): An Overview of Flood Concepts, Challenges, and Future Directions. In *J. Hydrol. Eng.* 27 (6), Article 03122001. DOI: 10.1061/(ASCE)HE.1943-5584.0002164.

Mississippi Coastal Map Revision Project (n.d.): Coastal Flood Mapping Process. Mississippi Coastal Map Revision Project. Available online at https://mscoastalmap.com/coastal-flood-mapping-process/.

Mizukami, Naoki; Newman, Andrew J.; Littell, Jeremy S.; Giambelluca, Thomas W.; Wood, Andrew W.; Gutmann, Ethan D. et al. (2022): New projections of 21st century climate and hydrology for Alaska and Hawaiʻi. In *Climate Services* 27, p. 100312. DOI: 10.1016/j.cliser.2022.100312.

Moftakhari, Hamed; Schubert, Jochen E.; AghaKouchak, Amir; Matthew, Richard A.; Sanders, Brett F. (2019): Linking statistical and hydrodynamic modeling for compound flood hazard assessment in tidal channels and estuaries. In *Advances in Water Resources* 128, pp. 28–38. DOI: 10.1016/j.advwatres.2019.04.009.

Mohammed, Ibrahim Nourein; Bomblies, Arne; Wemple, Beverley C. (2015): The use of CMIP5 data to simulate climate change impacts on flow regime within the Lake Champlain Basin. In *Journal of Hydrology: Regional Studies* 3, pp. 160–186. DOI: 10.1016/j.ejrh.2015.01.002.

Montaño, Jennifer; Coco, Giovanni; Antolínez, Jose A. A.; Beuzen, Tomas; Bryan, Karin R.; Cagigal, Laura et al. (2020): Blind testing of shoreline evolution models. In *Sci Rep* 10 (1), p. 2137. DOI: 10.1038/s41598-020-59018-y.

Moody, John A. (2012): An Analytical Method for Predicting Postwildfire Peak Discharges. In *Scientific Investigations Report* 2011 (5236). Available online at https://pubs.usgs.gov/sir/2011/5236/report/SIR11-5236.pdf.

Moritz, Heidi; White, Kate; Gouldby, Ben; Sweet, William; Ruggiero, Peter; Gravens, Mark; O'Brien, Patrick; Moritz, Hans; Wahl, Thomas; Nadal-Caraballo, Norberto C.; Veatch, Will (2015): USACE adaptation approach for future coastal climate conditions. In Proceedings of the Institution of Civil Engineers - Maritime Engineering. 168 (3), pp. 111-117. DOI: 10.1680/jmaen.15.00015.

Morris, Edward C. (1982): Mixed Population Frequency Analysis. US Army Corps of Engineers. Available online at https://www.hec.usace.army.mil/publications/TrainingDocuments/TD-17.pdf.

Musselman, Keith N.; Lehner, Flavio; Ikeda, Kyoko; Clark, Martyn P.; Prein, Andreas F.; Liu, Changhai et al. (2018): Projected increases and shifts in rain-on-snow flood risk over western North America. In *Nat. Clim. Chang.* 8 (9), pp. 808–812. DOI: 10.1038/s41558-018-0236-4.

NASA (2022): Interagency Sea Level Rise Scenario Tool. Available online at https://sealevel.nasa.gov/task-force-scenario-tool/.

National Snow and Ice Data Center (2022): Sea Ice Index. National Snow and Ice Data Center. Available online at https://nsidc.org/data/seaice_index, updated on 6/8/2022.

Natural Resources Wales (2021): Adapting to Climate Change. Guidance for Flood and Coastal Erosion Risk Management Authorities in Wales. Available online at https://gov.wales/sites/default/files/publications/2021-09/adapting-to-climate-change-guidance-for-flood-and-coastal-erosion-risk-management-authorities-in-wales.pdf.

Nature Climate Change Editorial Board (2020): Moving beyond isolated events. In *Nat. Clim. Chang.* 10 (7), p. 583. DOI: 10.1038/s41558-020-0846-5.

Naylor, Larissa A.; Spencer, Tom; Lane, Stuart N.; Darby, Stephen E.; Magilligan, Francis J.; Macklin, Mark G.; Möller, Iris (2017): Stormy geomorphology: geomorphic contributions in an age of climate extremes. In *Earth Surf. Process. Landforms* 42 (1), pp. 166–190. DOI: 10.1002/esp.4062.

Naz, Bibi S.; Kao, Shih-Chieh; Ashfaq, Moetasim; Gao, Huilin; Rastogi, Deeksha; Gangrade, Sudershan (2018): Effects of climate change on streamflow extremes and implications for reservoir inflow in the United States. In *Journal of Hydrology* 556, pp. 359–370. DOI: 10.1016/j.jhydrol.2017.11.027.

Neary, Daniel G.; Gottfried, Gerald J.; Folliott, Peter F. (2003): Post-wildfire watershed flood responses. Available online at https://postfiresw.info/sites/postfiresw.info/files/neary_2003.pdf.

Nerantzaki, Sofia D.; Papalexiou, Simon Michael (2022): Assessing extremes in hydroclimatology: A review on probabilistic methods. In *Journal of Hydrology* 605, p. 127302. DOI: 10.1016/j.jhydrol.2021.127302.

Neri, Andrea; Villarini, Gabriele; Napolitano, Francesco (2020): Statistically-based projected changes in the frequency of flood events across the U.S. Midwest. In *Journal of Hydrology* 584, p. 124314. DOI: 10.1016/j.jhydrol.2019.124314.

Nicholls, R. J.; Wong, P. P.; Burkett, V.; Codignotto, J.; Hay, J.; McLean, S. et al. (2007): Coastal systems and low-lying areas. Available online at https://ro.uow.edu.au/scipapers/164/.

NOAA (n.d.a): Extreme Water Levels. NOAA. Available online at https://tidesandcurrents.noaa.gov/est/, updated on 2014.

NOAA (n.d.b): National Tidal Datum Epoch. NOAA. Available online at https://tidesandcurrents.noaa.gov/datum-updates/ntde/, updated on 2020.

NOAA (n.d.c): New Datums: Replacing NAVD 88 and NAD 83. NOAA. Available online at https://geodesy.noaa.gov/datums/newdatums/index.shtml, updated on 2022.

NOAA (n.d.d): Tides & Great Lakes Water Levels. Available online at https://tidesandcurrents.noaa.gov/water_level_info.html.

NOAA (2017): NOAA ATLAS 14 POINT PRECIPITATION FREQUENCY ESTIMATES: KS. NOAA. Available online at https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html, updated on 2017.

NOAA (2021): National Data Buoy Center. NOAA. Available online at https://www.ndbc.noaa.gov/, updated on 8/10/2021.

NOAA (2022): Storm Events Database. NOAA. Available online at https://www.ncdc.noaa.gov/stormevents/, updated on 2022.

North Carolina Institute for Climate Studies; NOAA (n.d.): Precipitation Frequency. About. NCICS. Available online at https://precipitationfrequency.ncics.org/about.html.

Nott, David J.; Marshall, Lucy; Brown, Jason (2012): Generalized likelihood uncertainty estimation (GLUE) and approximate Bayesian computation: What's the connection? In *Water Resour. Res.* 48 (12). DOI: 10.1029/2011WR011128.

Ntelekos, Alexandros A.; Oppenheimer, Michael; Smith, James A.; Miller, Andrew J. (2010): Urbanization, climate change and flood policy in the United States. In *Climatic Change* 103 (3-4), pp. 597–616. DOI: 10.1007/s10584-009-9789-6.

NWS (n.d.): Hydrometeorological Design Studies Center. NOAA. Available online at https://www.weather.gov/owp/hdsc, updated on 2022.

NWS (2022): Analysis of Impact of Nonstationary Climate on NOAA Atlas 14 Estimates. National Weather Service. Available online at https://hdsc.nws.noaa.gov/hdsc/files25/NA14_Assessment_report_202201v1.pdf.

Olson, Scott A.; Simeone, Caelan E. (2021): Hydraulic Modeling at Selected Dam-Removal and Culvert-Retrofit Sites in the Northeastern United States. USGS (Scientific Investigations Report). Available online at https://pubs.er.usgs.gov/publication/sir20215056.

Over, Thomas M.; Saito, Riki J.; Soong, David T. (2016): Adjusting Annual Maximum Peak Discharges at Selected Stations in Northeastern Illinois for Changes in Land-use Conditions: U.S. Geological Survey Scientific Investigations Report 2016–5049. Available online at http://dx.doi.org/10.3133/sir20165049.

Pal, Sujan; Wang, Jiali; Feinstein, Jeremy; Yan, Eugene; Kotamarthi, Veerabhadra Rao (2022): Projected Increase in Hydrologic Extremes in the Mid-21st Century for Northeastern United States. In *Authorea*. May 11, 2022. DOI: 10.1002/essoar.10511327.1

Parris, Adam; Bromirski, Peter; Burkett, Virginia; Cayan, Dan; Culver, Mary; Hall, John et al. (2012): Global Sea Level Rise Scenarios for the US National Climate Assessment. NOAA. Available online at https://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf.

Passeri, Davina L.; Hagen, Scott C.; Plant, Nathaniel G.; Bilskie, Matthew V.; Medeiros, Stephen C.; Alizad, Karim. (2016): Tidal hydrodynamics under future sea level rise and coastal morphology in the Northern Gulf of Mexico. In *Earth's Future* 4(5), p. 159-176. DOI: 10.1002/2015EF000332.

Passeri, Davina L.; Bilskie, Matthew V.; Hagen, Scott C.; Mickey, Rangley C.; Dalyander, P. Soupy; Gonzalez, Victor M. (2021): Assessing the Effectiveness of Nourishment in Decadal Barrier Island Morphological Resilience. In *Water* 13 (7), p. 944. DOI: 10.3390/w13070944.

Plant, Nathaniel G.; Robert Thieler, E.; Passeri, Davina L. (2016): Coupling centennial-scale shoreline change to sea-level rise and coastal morphology in the Gulf of Mexico using a Bayesian network. In *Earth's Future* 4 (5), pp. 143–158. DOI: 10.1002/2015EF000331.

Praskievicz, Sarah (2015): A coupled hierarchical modeling approach to simulating the geomorphic response of river systems to anthropogenic climate change. In *Earth Surf. Process. Landforms* 40 (12), pp. 1616–1630. DOI: 10.1002/esp.3740.

Radke, Naomi; Keller, Klaus; Yousefpour, Rasoul; Hanewinkel, Marc (2020): Identifying decision-relevant uncertainties for dynamic adaptive forest management under climate change. In *Climatic Change* 163 (2), pp. 891–911. DOI: 10.1007/s10584-020-02905-0.

Ratajczak, Zak; Nippert, Jesse B.; Briggs, John M.; Blair, John M. (2014): Fire dynamics distinguish grasslands, shrublands and woodlands as alternative attractors in the Central Great Plains of North America. In *J Ecol* 102 (6), pp. 1374–1385. DOI: 10.1111/1365-2745.12311.

Raymond, Colin; Horton, Radley M.; Zscheischler, Jakob; Martius, Olivia; AghaKouchak, Amir; Balch, Jennifer et al. (2020): Understanding and managing connected extreme events. In *Nat. Clim. Chang.* 10 (7), pp. 611–621. DOI: 10.1038/s41558-020-0790-4.

Read, Laura K.; Vogel, Richard M. (2015): Reliability, return periods, and risk under nonstationarity. In *Water Resour. Res.* 51 (8), pp. 6381–6398. DOI: 10.1002/2015WR017089.

Reidmiller, David R.; Avery, Christopher W.; Easterling, David R.; Kunkel, Kenneth E.; Lewis, Kristin L.M.; Maycock, Thomas K.; Stewart, Brooke C. (2018): Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II. Available online at https://nca2018.globalchange.gov/.

Rengers, F. K.; McGuire, L. A.; Kean, J. W.; Staley, D. M.; Hobley, D. E. J. (2016): Model simulations of flood and debris flow timing in steep catchments after wildfire. In *Water Resour. Res.* 52 (8), pp. 6041–6061. DOI: 10.1002/2015WR018176.

Ries, Kernell G.; Newson, Jeremy K.; Smith, Martyn J.; Guthrie, John D.; Steeves, Peter A.; Haluska, Tana L. et al. (2017): Fact Sheet.

Rokaya, Prabin; Lindenschmidt, Karl-Erich; Pietroniro, Alain; Clark, Martyn (2022): Modelling of ice jam floods under past and future climates: A review. In *Journal of Hydrology X* 15, p. 100120. DOI: 10.1016/j.hydroa.2022.100120.

Rokaya, Prabin; Morales-Marín, Luis; Bonsal, Barrie; Wheater, Howard; Lindenschmidt, Karl-Erich (2019): Climatic effects on ice phenology and ice-jam flooding of the Athabasca River in western Canada. In *Hydrological Sciences Journal* 64 (11), pp. 1265–1278. DOI: 10.1080/02626667.2019.1638927.

Rosner, Ana; Vogel, Richard M.; Kirshen, Paul H. (2014): A risk-based approach to flood management decisions in a nonstationary world. In *Water Resour. Res.* 50 (3), pp. 1928–1942. DOI: 10.1002/2013WR014561.

Salas, J. D.; Obeysekera, J.; Vogel, R. M. (2018): Techniques for assessing water infrastructure for nonstationary extreme events: a review. In *Hydrological Sciences Journal* 63 (3), pp. 325–352. DOI: 10.1080/02626667.2018.1426858.

Sankovich, Victoria; Caldwell, R. Jason (2011): Extreme Storm Data Catalog Development. Department of the Interior. Denver, Colorado. Available online at https://www.usbr.gov/ssle/damsafety/TechDev/DSOTechDev/DSO-11-07.pdf.

Santiago-Collazo, Félix L.; Bilskie, Matthew V.; Hagen, Scott C. (2019): A comprehensive review of compound inundation models in low-gradient coastal watersheds. In *Environmental Modelling & Software* 119, pp. 166–181. DOI: 10.1016/j.envsoft.2019.06.002.

Saxe, Samuel; Hogue, Terri S.; Hay, Lauren (2018): Characterization and evaluation of controls on post-fire streamflow response across western US watersheds. In *Hydrol. Earth Syst. Sci.* 22 (2), pp. 1221–1237. DOI: 10.5194/hess-22-1221-2018.

Schlef, Katherine E.; François, Baptiste; Brown, Casey (2021): Comparing Flood Projection Approaches Across Hydro-Climatologically Diverse United States River Basins. In *Water Resour. Res.* 57 (1). DOI: 10.1029/2019WR025861.

Schlef, Katherine E.; François, Baptiste; Robertson, Andrew W.; Brown, Casey (2018): A General Methodology for Climate-Informed Approaches to Long-Term Flood Projection—Illustrated With the Ohio River Basin. In *Water Resour. Res.* 54 (11), pp. 9321–9341. DOI: 10.1029/2018WR023209.

Scottish Environment Protection Agency (2019): Climate change allowances for flood risk assessment in land use planning. Scottish Environment Protection Agency (1). Available online at https://research.fit.edu/media/site-specific/researchfitedu/coast-climate-adaptation-library/europe/united-kingdom-amp-ireland/SEPA.--2019.--CC-allowances-for-flood-risk-assessment-in-land-use-planning.pdf.

Serinaldi, Francesco; Kilsby, Chris G. (2015): Stationarity is undead: Uncertainty dominates the distribution of extremes. In *Advances in Water Resources* 77, pp. 17–36. DOI: 10.1016/j.advwatres.2014.12.013.

Serinaldi, Francesco; Kilsby, Chris G.; Lombardo, Federico (2018): Untenable nonstationarity: An assessment of the fitness for purpose of trend tests in hydrology. In *Advances in Water Resources* 111, pp. 132–155. DOI: 10.1016/j.advwatres.2017.10.015.

Sharma, Ashish; Wasko, Conrad; Lettenmaier, Dennis P. (2018): If Precipitation Extremes Are Increasing, Why Aren't Floods? In *Water Resour. Res.* 54 (11), pp. 8545–8551. DOI: 10.1029/2018WR023749.

Sharma, Sanjib; Lee, Ben Seiyon; Nicholas, Robert E.; Keller, Klaus (2021): A Safety Factor Approach to Designing Urban Infrastructure for Dynamic Conditions. In *Earth's Future* 9 (12). DOI: 10.1029/2021EF002118.

Sherwood, Christopher R.; Warrick, Jonathan A.; Hill, Andrew D.; Ritchie, Andrew C.; Andrews, Brian D.; Plant, Nathaniel G. (2018): Rapid, Remote Assessment of Hurricane Matthew Impacts Using Four-Dimensional Structure-from-Motion Photogrammetry. In *Journal of Coastal Research* 34 (6), p. 1303. DOI: 10.2112/JCOASTRES-D-18-00016.1.

Shimizu, Yasuyuki; Nelson, Jonathan (2007): International River Interface Cooperative (iRIC). International River Interface Cooperative. Available online at https://i-ric.org/en/about/.

Sholtes, Joel S.; Yochum, Steven E.; Scott, Julian A.; Bledsoe, Brian P. (2018): Longitudinal variability of geomorphic response to floods. In *Earth Surf. Process. Landforms* 43 (15), pp. 3099–3113. DOI: 10.1002/esp.4472.

Sklar, M. (1959): Fonctions de repartition a n dimensions et leurs marges. In *Publ. Inst. Statist. Univ. Paris* 8, pp. 229–231. Available online at https://cir.nii.ac.jp/crid/1573387449735953792.

Slater, Louise J.; Anderson, Bailey; Buechel, Marcus; Dadson, Simon; Han, Shasha; Harrigan, Shaun et al. (2021): Nonstationary weather and water extremes: a review of methods for their detection, attribution, and management. In *Hydrol. Earth Syst. Sci.* 25 (7), pp. 3897–3935. DOI: 10.5194/hess-25-3897-2021.

Slater, Louise J.; Singer, Michael Bliss; Kirchner, James W. (2015): Hydrologic versus geomorphic drivers of trends in flood hazard. In *Geophys. Res. Lett.* 42 (2), pp. 370–376. DOI: 10.1002/2014GL062482.

Small, David; Islam, Shafiqul; Vogel, Richard M. (2006): Trends in precipitation and streamflow in the eastern U.S.: Paradox or perception? In *Geophys. Res. Lett.* 33 (3). DOI: 10.1029/2005GL024995.

Smith, Adam B. (2020): U.S. Billion-dollar Weather and Climate Disasters, 1980 – present. Available online at https://www.ncei.noaa.gov/access/billions/.

Smith, M.P., Schiff, R., Olivero, A. and MacBroom, J.G. (2008): THE ACTIVE RIVER AREA: A Conservation Framework for Protecting Rivers and Streams. The Nature Conservancy. Boston, MA. Available online at https://asfpm-library.s3-us-west-2.amazonaws.com/General/TNC_Active_River_+Area_2008.pdf.

Spence, Caitlin M.; Brown, Casey M. (2018): Decision Analytic Approach to Resolving Divergent Climate Assumptions in Water Resources Planning. In *J. Water Resour. Plann. Manage.* 144 (9), p. 4018054. DOI: 10.1061/(ASCE)WR.1943-5452.0000939.

Srivastava, Abhishekh; Grotjahn, Richard; Ullrich, Paul A. (2020): Evaluation of historical CMIP6 model simulations of extreme precipitation over contiguous US regions. In *Weather and Climate Extremes* 29, p. 100268. DOI: 10.1016/j.wace.2020.100268.

Strupczewski, W. G.; Singh, V. P.; Mitosek, H. T. (2001): Non-stationary approach to at-site flood frequency modelling. III. Flood analysis of Polish rivers. In *Journal of Hydrology* 248 (1-4), pp. 152–167. DOI: 10.1016/S0022-1694(01)00399-7.

Sutton, Rowan T. (2019): Climate Science Needs to Take Risk Assessment Much More Seriously. In *Bulletin of the American Meteorological Society* 100 (9), pp. 1637–1642. DOI: 10.1175/BAMS-D-18-0280.1.

Sweet, W.V.; Kopp R.E.; Weaver, C.P.; Obeysekera, J.; Horton, R.M.; Thieler, E.R.; Zervas, C. (2017): *Global and Regional Sea Level Rise Scenarios for the United States*. NOAA Technical Report NOS CO-OPS 083. NOAA/NOS Center for Operational Oceanographic Products and Services. Available online at https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf.

Sweet, William V.; Hamlington, Benjamin D.; Kopp, Robert E.; Weaver, Christopher P.; Barnard, Patrick L.; Bekaert, David et al. (2022): *Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines*. Available online at https://aambpublicoceanservice.blob.core.windows.net/oceanserviceprod/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf.

Tang, Lei; Mo, Kangle; Zhang, Jianyun; Wang, Jun; Chen, Qiuwen; He, Shufeng et al. (2021): Removing tributary low-head dams can compensate for fish habitat losses in dammed rivers. In *Journal of Hydrology* 598, p. 126204. DOI: 10.1016/j.jhydrol.2021.126204.

Theuerkauf, Ethan J.; Braun, Katherine N.; Nelson, Danielle M.; Kaplan, Morgan; Vivirito, Salvatore; Williams, Jack D. (2019): Coastal geomorphic response to seasonal water-level rise in the Laurentian Great Lakes: An example from Illinois Beach State Park, USA. In *Journal of Great Lakes Research* 45 (6), pp. 1055–1068. DOI: 10.1016/j.jglr.2019.09.012.

Thibeault, Jeanne M.; Seth, Anji (2014): A Framework for Evaluating Model Credibility for Warm-Season Precipitation in Northeastern North America: A Case Study of CMIP5 Simulations and Projections. In *Journal of Climate* 27 (2), pp. 493–510. DOI: 10.1175/JCLI-D-12-00846.1.

Thieler, E. Robert; Hammar-Klose, Erika S. (1999): Open-File Report. In *Open-File Report* (99-593). DOI: 10.3133/ofr99593.

TMAC (2015): Future Conditions Risk Assessment and Modeling. FEMA. Available online at https://www.fema.gov/sites/default/files/documents/fema_tmac_2015_future_conditions_risk_assessment_modeling_report.pdf.

TMAC (2022): Annual Report. FEMA. Available online at https://www.fema.gov/sites/default/files/documents/fema_2021-technical-mapping-advisory-annual-report.pdf.

Todhunter, Paul E. (2012): Uncertainty of the Assumptions Required for Estimating the Regulatory Flood: Red River of the North. In *J. Hydrol. Eng.* 17 (9), pp. 1011–1020. DOI: 10.1061/(ASCE)HE.1943-5584.0000560.

Toro, Gabriel R.; Resio, Donald T.; Divoky, David; Niedoroda, Alan Wm.; Reed, Chris (2010): Efficient joint-probability methods for hurricane surge frequency analysis. In *Ocean Engineering* 37 (1), pp. 125–134. DOI: 10.1016/j.oceaneng.2009.09.004.

Touma, Danielle; Stevenson, Samantha; Swain, Daniel L.; Singh, Deepti; Kalashnikov, Dmitri A.; Huang, Xingying (2022): Climate change increases risk of extreme rainfall following wildfire in the western United States. In *Science advances* 8 (13), eabm0320. DOI: 10.1126/sciadv.abm0320.

Turcotte, Benoit; Morse, Brian; Pelchat, Gabriel (2020): Impact of Climate Change on the Frequency of Dynamic Breakup Events and on the Risk of Ice-Jam Floods in Quebec, Canada. In *Water* 12 (10), p. 2891. DOI: 10.3390/w12102891.

UK Government Environment Agency (2016): Flood risk assessments: climate change allowances. When and how local planning authorities, developers and their agents should use climate change allowances in flood risk assessments. UK Government, checked on 5/11/2020.

University of Maryland, Center for Disaster Resilience, and Texas A&M University, Galveston Campus, Center for Texas Beaches and Shores (2018): The Growing Threat of Urban Flooding: A National Challenge. College Park: A. James Clark School of Engineering. Available online at https://cdr.umd.edu/urban-flooding-report.

USACE (n.d.a): Engineer Manuals. US Army Corps of Engineers. Available online at https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/u43544q/636F617374616C20656E67696E656572696E67206D616E75616C/.

USACE (n.d.): HEC-SSP User's Manual. USACE. Available online at https://www.hec.usace.army.mil/confluence/sspdocs/sspum/latest.

USACE (n.d.b): Hydrologic Engineering Center. US Army Corps of Engineers. Available online at https://www.hec.usace.army.mil/software/hec-ras/.

USACE (1993a): Hydrologic Frequency Analysis. Engineer Manual 1110-2-1415. US Army Corps of Engineers. Available online at https://www.publications.usace.army.mil/portals/76/publications/engineermanuals/em_1110-2-1415.pdf.

USACE (1993b): River Hydraulics. Engineer Manual 1110-2-1416. US Army Corps of Engineers. Available online at https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-1416.pdf?ver=2013-09-04-070758-670.

USACE (2000): Planning Guidance Notebook. ER 1105-2-100. US Army Corps of Engineers. Available online at https://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/er_1105-2-100.pdf.

USACE (2015): North Atlantic Coast Comprehensive Study: Resilient adaptation to increasing risk. US Army Corps of Engineers. Available online at https://www.nad.usace.army.mil/CompStudy.aspx.

USACE (2018): Hydrologic Analysis of Interior Areas. Engineer Manual 1110-2-1413. US Army Corps of Engineers. Available online at https://www.publications.usace.army.mil/Portals/76/Users/227/19/2019/EM_1110-2-1413.pdf?ver=2018-09-13-125346-687.

USACE (2019): Incorporating Sea Level Change in Civil Works Programs. USACE. Washington, D. C. (Engineer Regulation, No. 1100-2-8162). Available online at https://www.publications.usace.army.mil/Portals/76/Users/182/86/2486/ER_1100-2-8162.pdf.

USACE (2020): River Analysis System (HEC-RAS) User's Manual. U.S. Army Corps of Engineers. Available online at https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest/foreword.

USACE (2021): South Atlantic Coastal Study (SACS) Main Report. U.S. Army Corps of Engineers. Available online at https://www.sad.usace.army.mil/SACS/.

USACE (2022): USACE Coastal Hazards System. U.S. Army Engineer Research and Development Center. Available online at https://chs.erdc.dren.mil/, updated on 2022.

USACE; USGS; State of Alabama (n.d.): Alabama Barrier Island Restoration Assessment. Available online at https://www.arcgis.com/apps/MapSeries/index.html?appid=ea29cd4e1f3b432e8c520df3fb7a9f8b, updated on 2022.

USGS (n.d. a): USGS Sea Level Change: An Interactive Guide to Global and Regional Sea Level Rise Scenarios for the United States. USGS. Available online at https://usgs.maps.arcgis.com/apps/Cascade/index.html?appid=668f6dc7014d45228c993302d3eab2f5.

USGS (n.d. b): USGS StreamStats. USGS. Available online at https://streamstats.usgs.gov/ss/.

USGS (2008): TNM Download v2. USGS. Available online at https://apps.nationalmap.gov/downloader/, updated on 2022.

USGS (2016a): 3D Elevation Program. USGS. Available online at https://www.usgs.gov/3d-elevation-program.

USGS (2016b): StreamStats. USGS. Available online at https://streamstats.usgs.gov/ss/, updated on 2022.

USGS (2017): Coastal Change Hazards Portal. USGS. Available online at https://marine.usgs.gov/coastalchangehazardsportal/.

USGS (2019): iRIC river flow and riverbed variation analysis. With assistance of Johnathan Nelson, Yasuyuki Shimizu. USGS. Available online at https://www.usgs.gov/software/iric-river-flow-and-riverbed-variation-analysis.

USGS (2021): Coastal Storm Modeling System (CoSMoS). USGS. Available online at https://www.usgs.gov/centers/pcmsc/science/coastal-storm-modeling-system-cosmos.

USGS; NOAA (n.d.): Total Water Level and Coastal Change Forecast Viewer. USGS; NOAA. Available online at https://coastal.er.usgs.gov/hurricanes/research/twlviewer/.

van Beusekom, Ashley E.; Viger, Roland J. (2018): A Physically Based Daily Simulation of the Glacier-Dominated Hydrology of the Copper River Basin, Alaska. In *Water Resour. Res.* 54 (7), pp. 4983–5000. DOI: 10.1029/2018WR022625.

Vidrio-Sahagún, Cuauhtémoc Tonatiuh; He, Jianxun (2022): The decomposition-based nonstationary flood frequency analysis. In *Journal of Hydrology* 612, p. 128186. DOI: 10.1016/j.jhydrol.2022.128186.

Villarini, G., S. Taylor, C. Wobus, R. Vogel, J. Hecht, K.D. White, B. Baker, K. Gilroy, J.R. Olsen, and D. Raff (2018): Floods and Nonstationarity: A Review. U.S. Army Corps of Engineers (CWTS, 2018-01).

Vitousek, Sean; Barnard, Patrick L.; Limber, Patrick; Erikson, Li; Cole, Blake (2017): A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. In *J. Geophys. Res.* 122 (4), pp. 782–806. DOI: 10.1002/2016JF004065.

Vitousek, Sean; Cagigal, Laura; Montaño, Jennifer; Rueda, Ana; Mendez, Fernando; Coco, Giovanni; Barnard, Patrick L. (2021): The Application of Ensemble Wave Forcing to Quantify Uncertainty of Shoreline Change Predictions. In *J. Geophys. Res.* 126 (7). DOI: 10.1029/2019JF005506.

Wagenbrenner, Joseph W.; Ebel, Brian A.; Bladon, Kevin D.; Kinoshita, Alicia M. (2021): Post-wildfire hydrologic recovery in Mediterranean climates: A systematic review and case study to identify current knowledge and opportunities. In *Journal of Hydrology* 602, p. 126772. DOI: 10.1016/j.jhydrol.2021.126772.

Wagner, Daniel M.; Krieger, Joshua D.; Veilleux, Andrea G. (2016): Scientific Investigations Report. Available online at https://pubs.er.usgs.gov/publication/sir20165081.

Wang, Ruo-Qian; Herdman, Liv M.; Erikson, Li; Barnard, Patrick; Hummel, Michelle; Stacey, Mark T. (2017a): Interactions of Estuarine Shoreline Infrastructure With Multiscale Sea Level Variability. In *J. Geophys. Res. Oceans* 122 (12), pp. 9962–9979. DOI: 10.1002/2017JC012730.

Wang, Wei; Li, Hong-Yi; Leung, L. Ruby; Yigzaw, Wondmagegn; Zhao, Jianshi; Lu, Hui et al. (2017b): Nonlinear Filtering Effects of Reservoirs on Flood Frequency Curves at the Regional Scale. In *Water Resour. Res.* 53 (10), pp. 8277–8292. DOI: 10.1002/2017WR020871.

Warner, Benjamin P.; Vogel, Eve; Hatch, Christine E. (2022): Exactly Where Does the River Need Space to Move? Seeking Participatory Translation of Fluvial Geomorphology into Flood Management. In *J Am Water Resour Assoc*, Article 1752-1688.13049. DOI: 10.1111/1752-1688.13049.

Wasko, Conrad; Westra, Seth; Nathan, Rory; Orr, Harriet G.; Villarini, Gabriele; Villalobos Herrera, Roberto; Fowler, Hayley J. (2021): Incorporating climate change in flood estimation guidance. In *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences* 379 (2195), p. 20190548. DOI: 10.1098/rsta.2019.0548.

Water Resources Council (1978): Guidelines for Implementing Executive Order 11988, Floodplain Management. Available online at https://www.ncpc.gov/docs/EO_11988_Implementing_Guidelines_1978.pdf.

Water Resources Council (2015): Guidelines for Implementing Executive Order 11988, Floodplain Management, and Executive Order 13690, Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input. Available online at https://www.fema.gov/sites/default/files/documents/fema_implementing-guidelines-EO11988-13690_10082015.pdf.

Weaver, C. P.; Moss, R. H.; Ebi, K. L.; Gleick, P. H.; Stern, P. C.; Tebaldi, C. et al. (2017): Reframing climate change assessments around risk: recommendations for the US National Climate Assessment. In *Environ. Res. Lett.* 12 (8), p. 80201. DOI: 10.1088/1748-9326/aa7494.

Werners, Saskia E.; Wise, Russell M.; Butler, James R.A.; Totin, Edmond; Vincent, Katharine (2021): Adaptation pathways: A review of approaches and a learning framework. In *Environmental Science & Policy* 116, pp. 266–275. DOI: 10.1016/j.envsci.2020.11.003.

Wing, Oliver E. J.; Bates, Paul D.; Smith, Andrew M.; Sampson, Christopher C.; Johnson, Kris A.; Fargione, Joseph; Morefield, Philip (2018): Estimates of present and future flood risk in the conterminous United States. In *Environ. Res. Lett.* 13 (3), p. 34023. DOI: 10.1088/1748-9326/aaac65.

Wobus, Cameron; Porter, Jeremy; Lorie, Mark; Martinich, Jeremy; Bash, Rachel (2021): Climate change, riverine flood risk and adaptation for the conterminous United States. In *Environ. Res. Lett.* 16 (9). DOI: 10.1088/1748-9326/ac1bd7.

Woltemade, Christopher J.; Hawkins, Timothy W.; Jantz, Claire; Drzyzga, Scott (2020): Impact of Changing Climate and Land Cover on Flood Magnitudes in the Delaware River Basin, USA. In *J Am Water Resour Assoc* 56 (3), pp. 507–527. DOI: 10.1111/1752-1688.12835.

Woodruff, Jonathan D.; Irish, Jennifer L.; Camargo, Suzana J. (2013): Coastal flooding by tropical cyclones and sea-level rise. In *Nature* 504 (7478), pp. 44–52. DOI: 10.1038/nature12855.

Working Group I (2021): Climate Change 2021: The Physical Science Basis. Intergovernmental Panel on Climate Change. Available online at https://www.ipcc.ch/report/ar6/wg1/.

Working Group II (2022): Climate Change 2022: Impacts, Adaptation and Vulnerability. Intergovernmental Panel on Climate Change. Available online at https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/.

Working Group III (2022): Climate Change 2022: Mitigation of Climate Change. Intergovernmental Panel on Climate Change. Available online at https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/.

World Climate Research Programme (2007): Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections. World Climate Research Programme. Available online at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/, updated on February 2021.

Wuebbles, D. J.; Fahey, D. W.; Hibbard, K. A.; Dokken, D. J.; Stewart, B. C.; Maycock, T. K. (2017): Climate Science Special Report: Fourth National Climate Assessment, Volume I. U.S. Global Change Research Program. Available online at https://science2017.globalchange.gov/.

Xiong, Bin; Xiong, Lihua; Guo, Shenglian; Xu, Chong-Yu; Xia, Jun; Zhong, Yixuan; Yang, Han (2020): Nonstationary Frequency Analysis of Censored Data: A Case Study of the Floods in the Yangtze River From 1470 to 2017. In *Water Resour. Res.* 56 (8). DOI: 10.1029/2020WR027112.

Yan, Lei; Xiong, Lihua; Guo, Shenglian; Xu, Chong-Yu; Xia, Jun; Du, Tao (2017): Comparison of four nonstationary hydrologic design methods for changing environment. In *Journal of Hydrology* 551, pp. 132–150. DOI: 10.1016/j.jhydrol.2017.06.001.

Yang, Long; Yang, Yixin; Villarini, Gabriele; Li, Xiang; Hu, Hongchang; Wang, Lachun et al. (2021): Climate More Important for Chinese Flood Changes Than Reservoirs and Land Use. In *Geophys. Res. Lett.* 48 (11). DOI: 10.1029/2021GL093061.

Yang, Wushuang; Xia, Runliang; Chen, Hua; Wang, Min; Xu, Chong-Yu (2022): The impact of calibration conditions on the transferability of conceptual hydrological models under stationary and nonstationary climatic conditions. In *Journal of Hydrology* 613, p. 128310. DOI: 10.1016/j.jhydrol.2022.128310.

Yochum, Steven E.; Sholtes, Joel S.; Scott, Julian A.; Bledsoe, Brian P. (2017): Stream power framework for predicting geomorphic change: The 2013 Colorado Front Range flood. In *Geomorphology* 292, pp. 178–192. DOI: 10.1016/j.geomorph.2017.03.004.

Yu, Guo; Wright, Daniel B.; Davenport, Frances V. (2022): Diverse Physical Processes Drive Upper-Tail Flood Quantiles in the US Mountain West. In *Geophys. Res. Lett.* 49 (10). DOI: 10.1029/2022GL098855.

Yu, Guo; Wright, Daniel B.; Zhu, Zhihua; Smith, Cassia; Holman, Kathleen D. (2019): Process-based flood frequency analysis in an agricultural watershed exhibiting nonstationary flood seasonality. In *Hydrol. Earth Syst. Sci.* 23 (5), pp. 2225–2243. DOI: 10.5194/hess-23-2225-2019.

Zarriello, Phillip J. (2017): Magnitude of flood flows at selected annual exceedance probabilities for streams in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2016–5156. DOI: 10.3133/sir20165156.

Zhang, Wei; Villarini, Gabriele; Vecchi, Gabriel A.; Smith, James A. (2018): Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston. In *Nature* 563 (7731), pp. 384–388. DOI: 10.1038/s41586-018-0676-z.

Zhu, Zhihua; Wright, Daniel B.; Yu, Guo (2018): The Impact of Rainfall Space-Time Structure in Flood Frequency Analysis. In *Water Resour. Res.* 54 (11), pp. 8983–8998. DOI: 10.1029/2018WR023550.

Zscheischler, Jakob; Martius, Olivia; Westra, Seth; Bevacqua, Emanuele; Raymond, Colin; Horton, Radley M. et al. (2020): A typology of compound weather and climate events. In *Nat Rev Earth Environ* 1 (7), pp. 333–347. DOI: 10.1038/s43017-020-0060-z.