A Conceptual Workflow for Projecting Future Riverine and Coastal Flood Hazards to Support the Federal Flood Risk Management Standard

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Abstract

In 2021, the reinstatement of the Federal Flood Risk Management Standard (FFRMS) required federally funded projects to recognize potential increases in flood hazards over their service lives due to climate change or local anthropogenic perturbations. Recognizing that the state of the science had advanced since the implementation guidelines for this standard were published in 2015 (WRC, 2015, Appendix H), an interagency state-of-the-science review committee conceptualized a workflow to guide the mapping and risk communication of projected future flood hazards in both riverine and coastal settings. This five-element workflow connects climate, hydrologic, and hydraulic models, incorporates land and water management impacts and ongoing geomorphic changes, and can be tailored to the unique nature of different agency needs and resources. These conceptual workflows also provide a basis for a Climate-Informed Science Approach implementation roadmap that identifies incremental steps for addressing the research and data gaps elucidated in our review. Many of these incremental steps present opportunities for interagency collaboration that would facilitate the rollout of the FFRMS in diverse riverine and coastal settings of the United States. We conduct case-study thought experiments to evaluate the implementation of the riverine and coastal workflows at three different locations in the United States: central Indiana, Galveston, Texas, and a small coastal community in western Alaska (Shaktoolik). Our thought experiments consider different project horizons, data availability, failure consequences, technical training requirements, and computational resources.

Introduction

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. 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 increased human suffering and flood damage due to climate change, 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). The Federal Flood Risk Management Standard (FFRMS), released on the same day as EO 13690 and revised in October of that year (see WRC, 2015, Appendix G), is intended to ensure that taxpayer-funded investments are resilient to current and future flooding, including climate-related impacts such as sea-level rise and more frequent and extreme precipitation. The FFRMS requires agencies to ensure investments are resilient to a higher flood standard, identified using one of three approaches:

1. **Climate-Informed Science Approach (CISA)** – The elevation and flood hazard area calculated using the best-available, actionable hydrologic and hydraulic data and methods that integrate current and future changes in flooding[1], including climate change and other physical processes (e.g., land-use change). The FFRMS implementation guidelines (WRC, 2015, Appendix H) state that this floodplain cannot be lower than the

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[1] EO 13690 requires the integration of current and future conditions when defining the CISA floodplain. This may either consist of the annual 1%-chance flood during the year of a project's service life when the anticipated flood hazards are most severe, or the flood anticipated to have an average annual exceedance probability of 1% during the entire service life.

base flood elevation (BFE) (flood with a 1% annual exceedance probability, a.k.a. 100-year flood).

2. **Freeboard Value Approach (FVA)** – The elevation and flood hazard area that result from adding an additional 2 feet to the 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.

Although EO 13690 gives Federal agencies discretion to select from among the three approaches, the FFRMS policy in 2015 stated that the CISA is preferred when data to support such an analysis are available (WRC, 2015, Appendix G). Federally funded projects covered by the Standard vary in their expected service life and criticality– from low-value accessory buildings and structures that may only last 5-10 years, to major physical infrastructure systems expected to serve community needs for 50 years or longer. The Standard was designed to provide flexibility to Federal agencies and their partners -- to consider and explicitly account for both the longevity and criticality of their investments when determining the flood hazards against which the projects will need to demonstrate resilience.

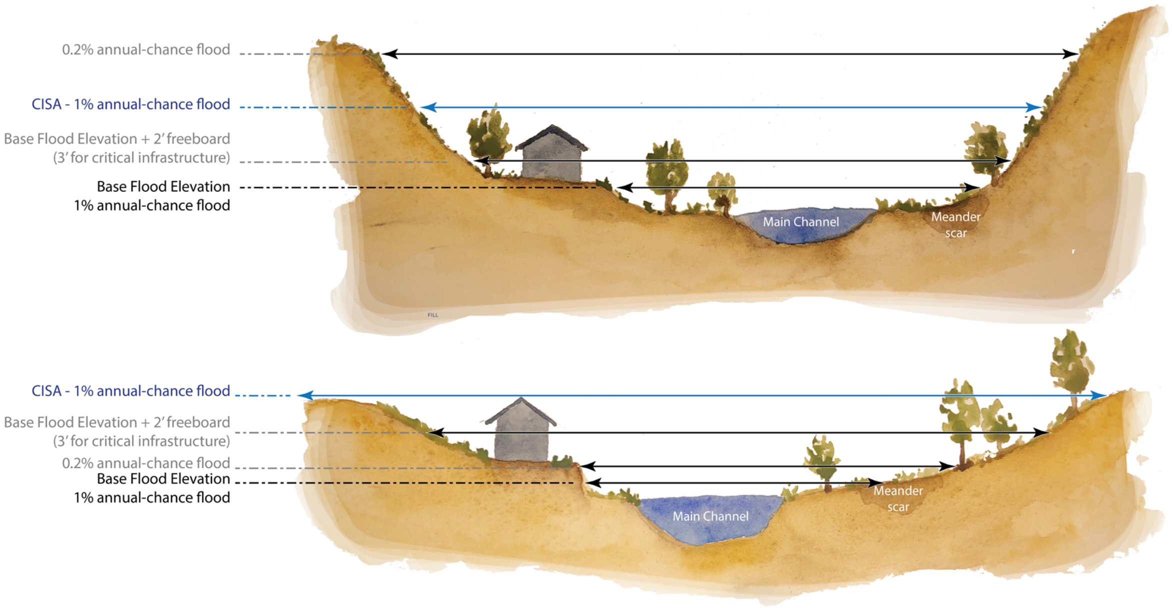

Figure 1: Hypothetical comparison of three floodplain definitions that the FFRMS permits relative to the base flood elevation (BFE) in different riverine geomorphic settings: narrower valley (top) and wider lowland floodplain (bottom) demonstrate differences in the relative height of these floodplain definitions in different settings.

Given the ongoing evolution of science supporting projections of current and future flood hazards, Section 4 of EO 13690 requires the Mitigation Framework Leadership Group to reassess the Standard annually in consultation with the Federal Interagency Floodplain Management Task Force after seeking stakeholder input. If warranted, they can recommend updates to the Water Resources Council (WRC) based on accurate and actionable science that accounts for changes in climate and other changes in flood hazards. Section 4 also specifies that the WRC should issue an update to the FFRMS at least once every five years.

To support a review of the state of the science following the reinstatement of EO 13690 in May 2021, the National Climate Task Force's Flood Resilience Interagency Working Group convened a multi-agency team of Federal experts to review science supporting the implementation of the FFRMS. Their principal product, a state-of-the-science (SotS) report, provides updated scientific concepts, data sources, methods, and considerations that complement the material published in the October 2015 CISA Appendix (WRC, 2015, Appendix G), including novel, generalized 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. In turn, this can inform new work that ultimately results in expanded availability and enhanced quality of data and models to support the implementation of the CISA option of the FFRMS in settings prone to riverine, coastal, pluvial, and compound flooding. As part of this collaboration, our multi-agency team developed two workflows to guide the implementation of the CISA option in riverine and coastal settings, as the science supporting flood projections is most actionable[2] in these two settings.

Conceptual Workflows

Our team has proposed workflows that are intended to provide Federal agencies with the key considerations for assessing different riverine and coastal flood hazards under different future scenarios. Key elements in this workflow are shown in Figures 2 and 3. These workflows are not intended to be prescriptive, but rather identify the major elements of flood hazard analyses and facilitate the identification of actionable science and methods for making future flood projections. These workflows are intended for any number of future scenarios, including changes in climate or other environmental conditions (e.g., land use and geomorphic change) that stakeholders may want to evaluate when assessing a project. Although the elements within the workflows are identified discreetly, there is significant interplay among them. During CISA implementation, regressive iterations are possible, even likely. The riverine and coastal workflows (Figures 2 and 3) share five common elements and a similar structure yet also recognize differences in flooding in these two settings.

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[2] Please consult the State of the Science report (FFRMS Science Subgroup, 2023) for criteria defining actionable science.

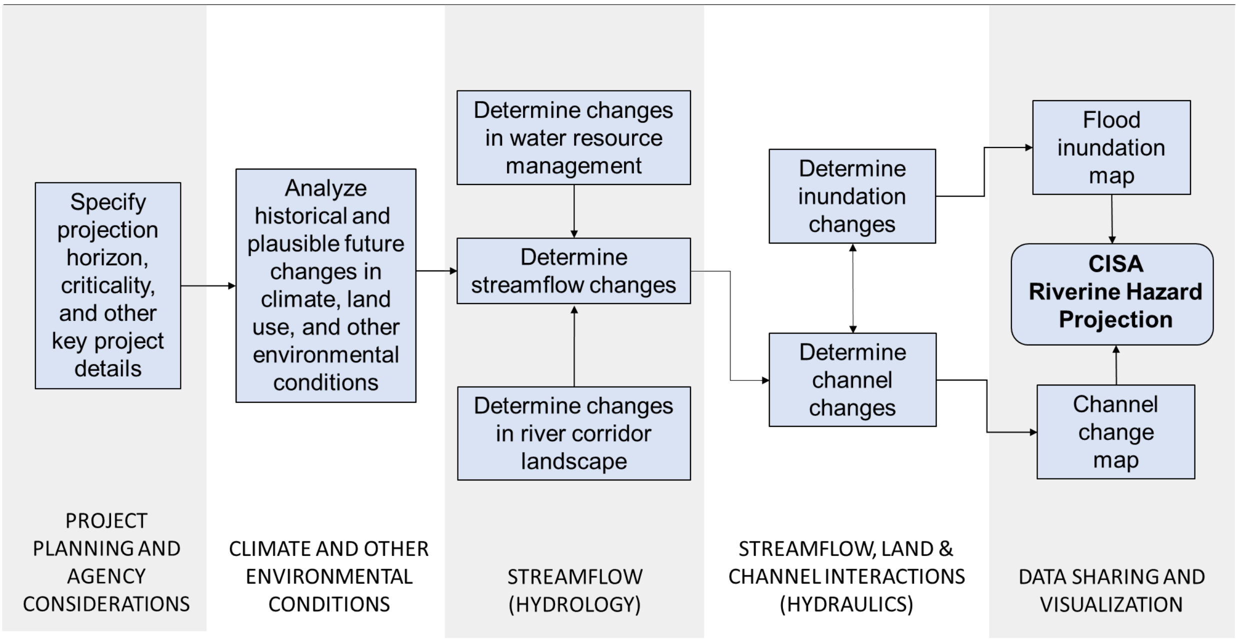

Figure 2: Conceptual workflow for projecting future riverine flood hazards

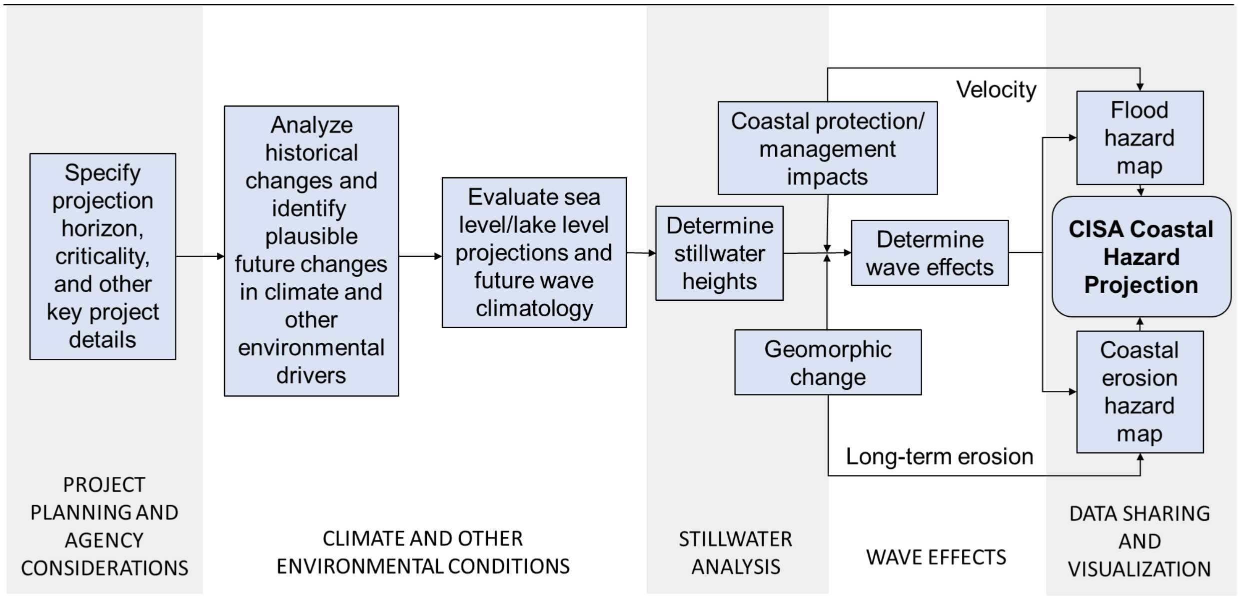

Figure 3: Conceptual workflow for projecting future coastal flood hazards

Both conceptual workflows commence with an assessment of project planning and agency considerations, including the service life and criticality of the project under consideration along with other agency-specific objectives. Second, historical and projected future changes in climate and other environmental drivers (e.g., urbanization) must be identified so that any future changes in flood hazards can be associated with specific drivers of change. The next two elements in both workflows involve estimating extreme water levels. The final element consists of communication of hazard projections, including creation of both inundation and erosion hazard maps. Often, inundation maps that consider current and projected climate and land-use-driven increases in floodplain water levels and the extent of inundation for a 1-percent annual-chance event assume a stable river channel or shoreline location. However, in many instances, ongoing fluvial and coastal erosion hazards may make additional areas susceptible to such flood events. For this reason, we have also added a geomorphic change content to both the riverine and coastal workflows.

Although both workflows share the same five core elements, the methods for estimating extreme water levels in the riverine and coastal Workflows are distinct. In the riverine workflow, elements 3 and 4 assess the effects of changes in climate (and other environmental drivers) on streamflow, including the mediating effects of any geomorphic and watershed management changes. Then, the effects of these changes on projected inundation extent are evaluated using hydraulic and/or hydrogeomorphic modeling. The extreme water-level estimation process in the coastal workflow first involves determining the stillwater elevation under climate change, including any mediating effects of geomorphic change or coastal management. Then, the additional effects of waves are considered in estimates of extreme total water levels.

Case-Study Thought Experiments

We conduct brief thought experiments to evaluate the potential for implementing the CISA at three locations using the riverine and coastal workflows. In particular, these thought experiments consider the current availability of data and actionable modeling approaches for making future flood projections with these workflows. They also identify limitations with current data and models and ways of addressing these challenges in the future.

Central Till Plain region, Indiana:

Our first thought experiment examines prospects for CISA implementation in riverine settings in the Central Till Plain physiographic region of central Indiana, including the Indianapolis metropolitan area. The state of Indiana has experienced some of the largest annual and extreme precipitation increases in the country (Angel et al. 2018; Widhalm et al. 2018), which are expected to continue through the 21st century (Hayhoe et al., 2018). Indiana has constructed a statewide floodplain information portal with flood hazard layers and is also one of the few states that has developed extensive processes for identifying fluvial erosion hazard (FEH) corridors that consider the lateral migration rates of channels (Burke Engineering LLC, 2018). Together, these characteristics make the Central Till Plain physiographic region of Indiana an excellent testbed for evaluating the CISA workflow for riverine hazard projections.

First, we would consider potential model chains linking different actionable approaches for assessing projected riverine hazards assuming a stable river channel using coupled physics-based simulation models and data-driven alternatives. One computationally intensive physics-based modeling chain involves (i) using downscaled and bias-corrected projections from General Circulation Models (GCMs) to drive watershed hydrology models (e.g., Distributed Hydrologic Soil Vegetation Model (DHSVM) or Sacramento Soil Moisture Accounting model (SAC-SMA)) and (ii) using estimated discharge time series to run a basin-scale two-dimensional hydraulic model (e.g., HEC-RAS 2D or TRITON) to predict inundation extent and depth (e.g., Dullo et al., 2021). An ensemble modeling approach considering variability in projections of greenhouse gas emissions and GCM selection could provide a means of addressing the climate-driven uncertainty of future flood projections.

Next, we would compare simulations for an unchanging channel from this physics-based model chain to data-driven alternatives. Schlef et al. (2021) conducted a split-sample experiment that suggested that data-driven statistical models using GCM-derived meteorological variables can project future flood hazards better than more intensive physics-based simulations, especially for regional predictions encompassing ungauged locations. We would also examine the extent to which recent data-driven models for adjusting design floods at gauged and ungauged locations to reflect current land-use conditions (e.g., Over et al., 2016; Hecht et al., 2022) could be leveraged to update design flood estimates to reflect current conditions to provide a reference point for CISA future flood estimates.

After considering the effects of climate change on flood hazards in a stable channel, we would then evaluate the potential impacts of channel change on future riverine hazards, including inundation and erosion. As a starting point, we could consider an actionable approach that Indiana has established for defining geomorphically active river corridor widths of potential lateral migration in meander belts relative to floodplain-confining characteristics of valley width and infrastructure. Currently, fluvial erosion hazard corridor widths range from three times the bankfull channel width for relatively stationary channels to eight times this width for actively migrating streams (Burke Engineering, LLC, 2018).

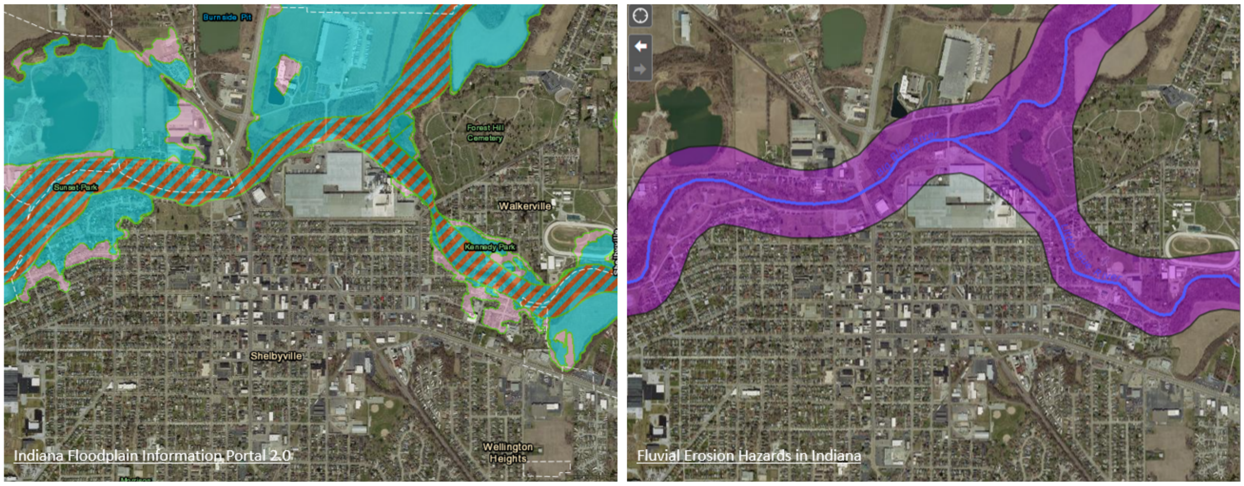

Figure 4: A comparison of the base flood elevation (elevation with a 1% annual chance of inundation) that FEMA uses for flood insurance rating maps (transparent blue areas on left image) with fluvial erosion hazard (FEH) corridors (transparent purple areas on right image) in and around Shelbyville, Indiana. Maps from Indiana Floodplain Information Portal 2.0 and Fluvial Erosion Hazards in Indiana hosted by the Indiana Department of Natural Resources.

We would need to ensure that a national approach for addressing geomorphic change could accommodate existing methods for delineating FEH corridors in Indiana based on channel bankfull widths and expected lateral migration in meander belts. These meander belt-based corridors include areas that could become flooded due to channel migration even if they remain outside of floodplains identified using coupled hydrologic-hydraulic simulations without any consideration of channel change, such as the 1% annual-chance floodplain shown on Flood

Insurance Rating Maps (FIRMs) (see Figure 4). Implementing this geomorphic change approach would also necessitate methods for integrating projected geomorphic changes into model chains simulating future flood hazards at both gauged and ungauged locations with different drainage areas and with different degrees of urbanization, including procedures for quantifying error propagation and cascading uncertainties. These opportunities include (i) combining future streamflow projections with existing regional models for estimating peak-flow frequencies (Rao, 2005) and hydraulic geometry (Robinson, 2013) at ungauged locations currently used in StreamStats (https://streamstats.usgs.gov/ss/) to project changes in channel capacity, bankfull widths, and FEH corridor width, and (ii) developing a continuous simulation modeling chain that couples climate, hydrologic and hydraulic models to examine geomorphic change. This modeling chain would utilize 2-D hydraulic model outputs (e.g., HEC-RAS 2D) of shear stress and flow velocities to identify geomorphic change under different climate scenarios (see Dullo et al., 2021 for another example). River-corridor hazard characteristics would need to be estimated over river networks and across regions using GIS-based mapping approaches (ASFPM Riverine Erosion Hazards Working Group, 2016; Sholtes et al., 2018) to consider the propagation of geomorphic change along river networks. Finally, the urban-to-rural gradient that overlies the Central Till Plain region would permit us to evaluate the extent to which urbanization modulates climate-driven hydrologic and geomorphic changes. Recognizing that the CISA also accommodates adjustments to design floods due to non-climatic drivers of change, actionable approaches for adjusting them for urbanization could be evaluated (e.g., NCHRP 15-61; Over et al., 2016).

Galveston, Texas:

Galveston, TX, located in the Western Gulf region of the United States, has historically experienced over 6 mm of sea level rise per year, equivalent to >0.6 m (2 ft) in the last 100 years (NOAA CO-OPS), one of the highest rates in the country. Mean relative sea level rise (RSLR) over the Western Gulf region is bounded by the intermediate to intermediate-high scenarios by 2050 when considering observed (1970-2020) and observationally extrapolated (2021-2050) RSLR (Sweet et al, 2022). In addition to high rates of expected sea level rise, Galveston is a highly developed barrier island with coastal structures like the Galveston Seawall, and high long-term rates of annual shoreline erosion (>2m/year) along the middle portion of the island (Himmlestoss et al., 2017, Morton, et al, 2004). On Galveston Island, for example, the East Beach area adjacent to the jetty advanced at a net rate of 3.66 m/yr (12.0 ft/yr) between the 1930s and 2019, whereas Galveston Island shorelines west of the seawall retreated at average net rates of 0.93 m/yr (3.0 ft/yr) during the same period (Paine, et al. 2021).

A new federal action/project using the Coastal CISA workflow would first identify the project factors that would influence decision making, including project life, criticality, and resource availability, as well as the physical factors that may have an influence on the project: increased stillwater elevation due to sea level rise, the impact of waves, the presence and proximity of coastal structures, and the proximity to potentially retreating shorelines. Even on Galveston Island, not every one of these physical factors may have direct influence on a project, depending on the location. Following this step, RSLR projections would be determined based on the project life. Short term actions (<30 years) would use the RSLR scenario curve (Sweet et al, 2022) immediately above the regional observational extrapolation to account for uncertainty (in this case, the Intermediate High scenario). Longer term actions (>30 years) would use at least two SLR planning scenarios to accommodate different risk tolerances. For highly critical actions, a RSLR scenario more severe than an extrapolated curve from a model fit to observations would be used. The purpose of using at least two scenarios is to make sure to address 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 could reduce potential overdesign consequences and gives flexibility for deciding which scenario is best, based on agency methods for determining the scale and consequence of the action. Following the procedure described in the SotS report, the user would select the two RSLR scenarios that bound the extrapolated curve from both above and below. For this example, those curves would be the Intermediate High and the Intermediate scenarios. These scenarios can then be extended beyond 2050 (out as far as 2150) as planning scenarios for highly critical and less critical actions, respectively.

Depending on project needs and constraints, there are a number of ways that these SLR scenarios could be integrated for climate informed projects ranging from simple to complex:

- RSLR conditions could be combined with appropriate design water levels or FEMA flood insurance study (FIS) values to provide elevation and depth information
- Hydrodynamic models could be developed or modified to incorporate RSLR through direct analysis – either for a design event or for more comprehensive response=based statistics such as multiple return periods.
- The influence of RSLR can be evaluated with respect to wave impacts (overland propagation, runup and overtopping of coastal structures and features).
- The influence of RSLR can be evaluated with respect to long term shoreline change projections or modeling, which could be integrated back into the hydrodynamic modeling.

Galveston, TX is a well-studied portion of the coastline, and existing hydrodynamic, wave, morphodynamic and statistical modeling frameworks useful for projecting future flood hazards are widely available from USACE regional studies, FEMA FIS studies, and a number of state, local (City of Galveston, 2012) and university projects (Morton and McKenna, 1999).

Some considerations for Galveston, TX are the presence of large shoreline stabilization and flood protection structures and the influence of those structures on a proposed project and the high rates of shoreline change and RSLR. For a critical project influenced by these factors, a more complex evaluation may be necessary. Notably, for projects influenced by runup and overtopping of a coastal feature, simple linear superposition of RSLR is not appropriate and more dynamic modeling and analysis is necessary. This could be performed by integrating RSLR into stillwater elevations and performing detailed runup or overtopping analyses using a number of different methods depending on the site conditions. Many of these methods and uses are detailed in FEMA mapping guidance. This is because increases in water levels from future sea level rise may cause a nonlinear response to wave runup and thus higher BFEs in these areas (Figure 5).

Figure 5: Waves runup on the Galveston Seawall and the 1900 Galveston Hurricane memorial before the arrival of Hurricane Ike (courtesy Johnny Hanson, Houston Chronicle) (from NOAA, 2009)

Depending on resources and project specific conditions, a simpler evaluation may be sufficient. The workflow is designed to identify those decision points and guide the user in making the decisions necessary.

Shaktoolik, Alaska:

Very data-poor regions of the country will be challenged to implement the FFRMS. Moreover, some data-poor communities are located in settings where important flood-generating processes are not accounted for in many Federal policies and guidelines. To assess the feasibility of CISA implementation in such places, we conducted a case-study thought experiment in Shaktoolik, a small Alaska Native community (population 214–2021; DCRA). Sea ice is a major influence on extreme water levels in Shaktoolik (Golder Associates Ltd., 2020), which is located on a gravel barrier spit fronting Shaktoolik Bay and along the outlet of the Tagoomenik River. During Ex-Typhoon Merbok in 2022, Shaktoolik experienced the highest documented flood water levels from the event (High Water Mark Viewer) due to the funneling of storm surge into the confined embayment of Norton Sound. An engineered gravel storm protection berm fronting the community eroded completely but did not breach. Woody debris was transported atop the upper threshold of the berm near and around the base of structures by waves (Figure 6). Ex-Typhoon Merbok was on par with a storm in October of 1960, making it roughly akin to an event with a 2% annual exceedance probability (a.k.a. a 50-year event) if the historical record is assumed to be stationary (Overbeck and Buzard, 2020). RSLR exacerbates the effects of extreme water levels that impact the area during storms. This region of western Alaska has experienced 3.89 mm of sea level rise per year since 1992, an equivalent of 0.12 m (0.38 ft) in the last 30 years (NOAA CO-OPS). Along the section of coast fronting community infrastructure, a long-term net rate of annual shoreline erosion which averages out episodic erosion from storms, is +/- 0.30 m/yr (1 ft/yr), computed between 1950 and 2015 (Overbeck et al., 2020).

Figure 6: Shoreline change in Shaktoolik following Ex-Typhoon Merbok in September 2022.

(Photo by Gloria Andrew, resident of Shaktoolik)

Shaktoolik has multiple and conflicting 1-percent-annual-chance flood estimates and there is no published BFE for use in a Freeboard Value Approach. In 2011, the U.S. Army Corps of Engineers produced a flood study at Shaktoolik, which used an unvalidated model-based approach including a Ranked Plotting Method applied to model estimates of wind, wave, and surge values over a 56-year hindcast (1954-2009). Wind, wave, and surge models included WAve prediction Model (WAM), ADvanced CIRCulation Model (ADCIRC), and the Storm-induced BEAch Change Model (SBEACH) (USACE, 2011) with estimates of wind drag roughness due to the presence of sea ice as modeled by Chapman et al. (2009). Since model results were not calibrated or validated with any locally collected data, a double accounting of wave setup was released in this report. Moreover, this study did not recognize changes in conditions when determining the 1-percent-annual-chance flood elevation nor did it consider future flood hazards that considered climate change projections. This was also the only available flood study for Shaktoolik until the Native Village of Shaktoolik initiated a building-scale flood study with a private industry firm (Golder Associates Ltd., 2020) that computed time-specific flood elevations for events with annual exceedance probabilities ranging from 1-50%, i.e., return periods ranging from 2 to 100 years.

Many aspects of the Golder Associates Ltd. (2020) study exemplify the CISA coastal workflow and provide a blueprint for similar studies in other coastal communities in rural Alaska that are confronting increased coastal flood hazards. Key components of this study that were not completed as a part of the USACE study were considerations of climate drivers (e.g., RSLR and sea ice changes), actionable results (e.g., the resulting mapped products and local data used for calibration and validation), and updates to baseline mapped data (e.g., historical flood heights, topography, bathymetry, and cross-shore profiles). Components of the model approach included using Monte Carlo simulations and peaks-over-threshold frequency analysis techniques, the Delft3D-WAVE model, EurOtop (van der Meer 2018) wave runup calculations, and RSLR projection from a nearby (125 miles away) NOAA tide station adjusted with a local datum shift (NOAA CO-OPS). The model considers multiple climate scenarios, examines changes in coastal flood hazards due to rising sea levels, changing storm conditions, and ongoing erosion. It also includes other environmental drivers besides temperature and precipitation that are locally important for flood hazards including wind, sea ice, and permafrost thaw (element 2). Improved baseline data were critical to calibrating and validating model results making them actionable for the community of Shaktoolik. In particular, a storm record (26 maximum storm high water mark estimates; Overbeck and Buzard, 2020 and Kinsman and DeRaps, 2012) was used to create an extreme value analysis and to validate wave runup heights, which highlighted the discrepancy between USACE (2011) and Golder Associates Ltd. (2020) model results. Ultimately, the Golder model provided estimates of coastal floods with annual exceedances probabilities of 0.5 to 0.01 (2 to 100-year return periods) under current conditions, as well as ones projected in 2050 and 2100 under three climate scenarios. While there is not an established BFE to serve as a lower bound for the CISA floodplain elevation estimate, most coastal locations, including Shaktoolik, are experiencing increasing RSLR rates. In such settings, a BFE is not a prerequisite for a CISA floodplain.

Most model studies could be improved with the availability of new baseline datasets which are emerging rapidly for Alaska. Shaktoolik is representative of a broader region of communities with a paucity of source data primarily due to minimal participation or the inability to participate in the National Flood Insurance Program. In addition to FEMA FIRMs and BFEs, these data limitations include underlying geospatial, environmental, historical event data, flood monitoring systems, baseline topography and bathymetry, climatological records, or previous studies for other components of flood and erosion assessments that can be employed in FFRMS workflows. In areas where the State of Alaska has helped make baseline topography, imagery, and elevation data publicly available (State of Alaska Data Catalog) or where new baseline data collection can be conducted, these data can be incorporated into a CISA-driven assessment. To this end, advances in national datasets, such as Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) topobathy lidar (access data through the NOAA Digital Coast) or RSLR scenarios (Sweet et al., 2022) are being extended to the Alaskan coastline, making CISA more feasible. To improve the implementation of the CISA, issues with wave validation would need to be resolved, perhaps with the installation of wave buoys. Real-time and historical water levels are available from an in-region collaboration known as the Alaska Water Level Watch. RSLR scenarios from Sweet et al. (2022) can also be applied, but are reliant on datum conversion values maintained by the State of Alaska's Tidal Datum Conversion Tool, as NOAA's VDatum tool is not yet developed statewide.

Areas subject to flooding in places like Alaska, which are experiencing rapid and irreversible impacts due to climate change, such as reduced permafrost and seasonal sea ice, are therefore particularly suited for CISA despite the added data and research needed to support the workflows. Beyond individual project design, risk communication is key, as many Alaska Native communities seek these studies out to determine their climate adaptation pathway (e.g., protect in place, managed retreat, relocation) and to provide the data to Congress or another entity to justify funding for the selected adaptation pathway (a multitude of agencies provide services to communities) (e.g., Bronen and Chapin, 2013).

An interagency roadmap for supporting CISA implementation:

Our thought experiments elucidate numerous ideas for improving the decision-support tools currently being developed to guide the implementation of the FFRMS. In particular, they elucidate data and modeling needs that could be addressed in coming years. The list below summarizes some key advances to prioritize for supporting the implementation of the Federal Flood Risk Management Standard, including ones elucidated in our three thought experiments as well as others identified in the SotS report (FFRMS Science Subgroup, 2023):

- Continue improving scenario-based planning approaches, including:
  - Precipitation and temperature scenarios for extreme water-level events
  - Land-use change scenarios
  - Following regular updating process for mean sea-level rise scenarios (global, regional and global) outlined in Sweet et al. (2022)
  - Methods for evaluating multiple plausible scenarios
- Compare data-driven and physically based modeling of future flood hazards under different data and model availability circumstances
- Integrate geomorphic change into future flood hazard analyses in diverse riverine and coastal settings, including effects of human-made structures and their maintenance, through data-driven and physical models.
- Improve our understanding of the ways in which urbanization may mediate climate impacts to flood hazards
- Improve representations of hydraulics and hydrodynamics (expanding use of 2-D riverine hydraulic models where appropriate, overland wave conditions, effects of sea ice on waves in Alaska)
- Improve representation of cold-region hazards, including sea ice, river ice jams, permafrost, and glacial melt in flood hazard assessments
- Incorporate vertical land motion and high-resolution topographic and bathymetric data into models and maps of inundation and geomorphic hazards
- Reduce uncertainty of extreme precipitation events and high water-level projections for Great Lakes
- Produce CISA maps showing inundation and geomorphic hazards:
  - Develop a transitional product to determine if proposed Federal actions will occur within the CISA floodplain (future 1-percent-annual-chance floodplain) that shows the future horizontal extent of flooding and the vertical change in the BFE.
  - Produce inundation maps that communicate inundation probabilities that can inform agencies of percent likelihood of inundation in addition to whether they are within the CISA floodplain (would build off FEMA FFRD efforts).
  - Enhance mapping of geomorphic hazards (channel change, erosion) including semi-automated mapping of river channel degradation, aggradation and widening, through state/regional fluvial erosion hazard techniques
- Expand resources available for areas without FEMA FIRMs, including possible pursuit of pilot study mapping of inundation on agency-owned lands
- Develop similar workflows for CISA implementation in areas prone to pluvial and compound flood hazards

- Establish procedures that account for the propagation of errors and uncertainty through the model chains that develop from the conceptual workflow blueprints.
- Identify case studies for testing CISA implementation for riverine, coastal, pluvial, and compound flooding.

Greater collaboration and cooperation among federal and non-federal partners could further support the implementation of the FFRMS.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Angel, J., C. Swanston, B.M. Boustead, K.C. Conlon, K.R. Hall, J.L. Jorns, K.E. Kunkel, M.C. Lemos, B. Lofgren, T.A. Ontl, J. Posey, K. Stone, G. Takle, and D. Todey, 2018: Midwest. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 872–940. https://doi.org/10.7930/NCA4.2018.CH21

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

Bronen, R. and F.S. Chapin III. 2013. “Adaptive governance and institutional strategies for community relocation in Alaska.” *Proc. Natl. Acad. Sci. U.S.A*, 110(23), 9320-9325, https://doi.org/10.1073/pnas.1210508110.

Burke Engineering, LLC, 2018. “Indiana fluvial erosion hazard mitigation manual.” Indiana Silver Jackets Hazard Mitigation Task Force https://feh.iupui.edu/

Chapman, R.S., Kim, S-C, and Mark, D. J. for U.S. Army Corps of Engineers, Alaska District, 2009. “Storm damage and flooding evaluation, storm-induced water level prediction study for the western coast of Alaska.” Vicksburg, MS, U.S. Army Engineering Research and Development Center, Coastal & Hydraulics Laboratory, 92 p.

City of Galveston Department of Planning & Community Development. 2012. City of Galveston Erosion Response Plan, 37p. https://www.galvestontx.gov/601/Planning-Development-Division

Dullo, T.T., Darkwah, G.K., Gangrade, S., Morales-Hernández, M., Sharif, M.B., Kalyanapu, A.J., Kao, S.-C., Ghafoor, S., and Ashfaq, M. 2021. “Assessing climate-change-induced flood risk in the Conasauga River watershed - an application of ensemble hydrodynamic inundation modeling.” *Nat. Hazards Earth Syst. Sci.*, 21, 1739-1757, https://doi.org/10.5194/nhess-21-1739-2021.

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-.

Federal Flood Risk Management Standard (FFRMS) Science Subgroup of the Flood Resilience Interagency Working Group of the National Climate Task Force. 2023. Federal Flood Risk Management Standard Climate-Informed Science Approach (CISA) State of the Science Report, 106 p., https://www.whitehouse.gov/wp-content/uploads/2023/03/Federal-Flood-Risk-Management-Standard-Climate-Informed-Science-Approach-CISA-State-of-the-Science-Report.pdf.

Golder Associates Ltd. 2020. Climate Change Vulnerability and Risk Assessment Shaktoolik, Alaska: submitted to Native Village of Shaktoolik.

Hayhoe, K., D.J. Wuebbles, D.R. Easterling, D.W. Fahey, S. Doherty, J. Kossin, W. Sweet, R. Vose, and M. Wehner. 2018. "Our Changing Climate. In Impacts, Risks, and Adaptation in the United States." Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and Stewart, B.C. (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 72–144. https://doi.org/10.7930/NCA4.2018.CH2.

Hecht, J.S., Barth, N.A., Ryberg, K.R., and Gregory, A.E. 2022. "Simulation experiments comparing nonstationary design-flood adjustments based on observed annual peak flows in the conterminous United States." *J. Hydrol. X.*, https://doi.org/10.1016/j.hydroa.2021.100115.

Himmelstoss, E.A., Kratzmann, M.G., and Thieler, E.R. 2017. "National assessment of shoreline change—summary statistics for updated vector shorelines and associated shoreline change data for the Gulf of Mexico and Southeast Atlantic coasts." U.S. Geological Survey Open-File Report 2017–1015, 8 p., https://doi.org/10.3133/ofr20171015.

Kinsman, N.E.M., and DeRaps, M.R., 2012, "Coastal hazard field investigations in response to the November 2011 Bering Sea storm, Norton Sound, Alaska." Alaska Division of Geological & Geophysical Surveys Report of Investigation 2012-2 v. 1.1, 51 p., 1 sheet. https://doi.org/10.14509/24484.

Morton, R.A., Miller, T.L., and Moore, L.J. 2004. "National assessment of shoreline change: Part 1: Historical shoreline changes and associated coastal land loss along the U.S. Gulf of Mexico." U.S. Geological Survey Open-file Report 2004-1043, 45p.

Morton, R. A., & McKenna, K. K. 1999. "Analysis and projection of erosion hazard areas in Brazoria and Galveston Counties, Texas." *J. Coastal Res.*, 106–120. http://www.jstor.org/stable/25736190

National Cooperative Highway Research Program (NCHRP). 2018. "Applying climate change information to hydrologic and coastal design of transportation infrastructure." Project 15-61, Final Report. https://onlinepubs.trb.org/Onlinepubs/nchrp/docs/NCHRP1561FinalReport_rev.pdf

National Oceanic and Atmospheric Administration (NOAA). 2009. Tropical Storm Report: Hurricane Ike, Robbie Berg, National Hurricane Center, 55p. https://www.nhc.noaa.gov/data/tcr/AL092008_Ike.pdf

Over, T.M. 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, 33p. https://pubs.er.usgs.gov/publication/sir20165049

Overbeck, J.R., and Buzard, R.M. 2020. RE: Coastal flood and erosion data request. Division of Geological & Geophysical Surveys, Department of Natural Resources.

Overbeck, J.R., Buzard, R.M., Turner, M.M., Miller, K.Y., and Glenn, R.J., 2020. “Shoreline change at Alaska coastal communities.” Alaska Division of Geological & Geophysical Surveys Report of Investigation 2020-10, 29 p., 47 sheets. https://doi.org/10.14509/30552

Paine, J.G., Caudle, T., and Andrews, J.R., 2021, Shoreline movement and beach and dune volumetrics along the Texas Gulf Coast, 1930s to 2019.” Bureau of Economic Geology Report https://coastal.beg.utexas.edu/shorelinechange2019/assets/glo_gsu_2019_r02_d4.pdf

Rao, A.R. 2005. “Flood-frequency relationships for Indiana.” Joint Transportation Research Program, Purdue University, FHWA/IN/JTRP-2005/18, 14 p.

Reidmiller, D.R, Avery, C.W., Easterling, D.R, Kunkel, K.E., Lewis, K.L.M., Maycock, T.K., and Stewart, B.C. 2018. “Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II.”

Robinson, B. 2013. Regional bankfull-channel dimensions of non-urban wadeable streams in Indiana.” U.S. Geological Survey Scientific Investigations Report 2013-5078, 33 p.

Sholtes, J.S., Yochum, S.E., Scott, J.A., and Bledsoe, B.P. 2018. Longitudinal variability of geomorphic response to floods. *Earth Surf. Proc. Land.*, https://doi.org/10.1002/esp.4472

Smith, A.B. 2020. U.S. Billion-dollar Weather and Climate Disasters, 1980 - present (NCEI Accession 0209268).

Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak. 2022. “Global and regional sea level rise scenarios for the United States: updated mean projections and extreme water level probabilities along U.S. Coastlines.” NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nostechrpt01-global-regional-SLR-scenarios-US.pdf

United States Army Corps of Engineers (USACE). 2011. “Shaktoolik coastal flooding analysis” Denali Commission Alaska. Available online at https://cf.denali.gov/Data/attachments/Shaktoolik_Report_FINAL.pdf.

van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P. and Zanuttigh, B., 2018. "EurOtop: Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application." https://www.overtopping-manual.com

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

Widhalm, M., Hamlet, A. Byun, K., Robeson, S., Baldwin, M., Staten, P., Chiu, C., Coleman, J., Hall, B., Hoogewind, K., Huber, M., Kieu, C., Yoo, J., Dukes, J.S. 2018. "Indiana's past and future climate: a report from the Indiana Climate Change Impacts Assessment." Purdue Climate Change Research Center, Purdue University. West Lafayette, Indiana. https://bit.ly/2KDsaga

Wigmosta, M.S., Vail, L., Lettenmaier, D.P. 1994. "A distributed hydrology-vegetation model for complex terrain", *Water Resour. Res.*, 30, 1655-1679.

Wuebbles, D. J., Fahey, D. W., Hibbard, K. A., Dokken, D. J., Stewart, B. C., and Maycock, T. K. 2017. Climate Science Special Report: Fourth National Climate Assessment, Volume I. U.S. Global Change Research Program.