NIST Grant/Contractor Report
NIST GCR 24-056

Incorporating Climate Projections into Infrastructure Planning and Design

Comprehensive report from a series of virtual workshops convened by NIST-NOAA-ASCE

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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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Executive Summary

Communities across the United States are experiencing adverse impacts from climate change, and these impacts are only expected to worsen in the future. To ensure that communities and their built environments are resilient to current and future climate impacts, the National Institute for Standards and Technology (NIST), the National Oceanic and Atmospheric Administration (NOAA), and the American Society for Civil Engineers (ASCE) partnered to convene a series of three workshops focused on how communities are incorporating climate projections into their infrastructure planning. The workshop series provided a unique opportunity to convene practitioners who are actively developing and/or implementing climate-resilient design guidelines to share best practices, lessons learned, and challenges. Although challenges and gaps remain, the workshop series helped clarify current leading practices for developing and implementing climate-resilient infrastructure guidelines.

Each of the three workshops focused on one of the following climate hazards: sea level rise and coastal storm surge; rain and urban inland flooding; and wildfire and urban planning. To better understand the current state of practice for resilient infrastructure design for different hazards, each workshop included three case study presentations from practitioners across the U.S. These case studies highlighted different methods for incorporating climate science information into infrastructure planning and design based on hazard. Key takeaways from each workshop are presented below:

- **Sea Level Rise and Coastal Storm Surge:**
    - Guidelines include both likely and high-end sea level rise projections for multiple time periods (near-, medium-, and long-term).
    - Guidelines incorporate local/regional projections where possible and adapt global projections for regional applications if local/regional projections are not available.
    - Design life, criticality, and investment level are the key considerations for selecting which sea level rise projection and Shared Socioeconomic Pathway/Representative Concentration Pathway (SSP-RCP) scenario to use when designing a project.
    - Approaches for incorporating sea level rise into project design vary between case studies. Some guidelines focus on calculating future sea level rise-adjusted elevations whereas others encourage more holistic vulnerability assessments to prioritize adaptation strategies.
- **Rain and Inland Urban Flooding:**
    - Most practitioners need future-adjusted intensity-duration-frequency (IDF) curves to incorporate precipitation projections into hydraulic modeling and stormwater infrastructure design.
    - There are a range of different methods to model local future rain events and develop future-adjusted IDF curves, such as applying delta change factors to historical precipitation data or Atlas 14 curves, or completing more complex simulation models of future flood events.

  - Accurately capturing local conditions in precipitation projections is especially important for developing guidelines.
  - Given the short timescales over which extreme rainfall events can occur, practitioners need sub-daily precipitation projections, but climate models cannot simulate such events. Extrapolating sub-daily values from daily data means that sub-daily IDF curves will remain highly uncertain.
- **Wildfire and Urban Planning:**
  - Given the significant and extensive damage wildfires are already causing across the U.S., most practitioners focus on developing hazard mitigation techniques and integrating wildfire resilience considerations into urban planning rather than developing and using future climate projections for planning.
  - Wildfire resilience requires a systemic approach, including incorporating wildfire considerations into building codes and land use plans and facilitating implementation of mitigation techniques through targeted assessments and programs.

In addition to the hazard-specific findings summarized above, the workshop series helped identify cross-cutting leading practices for incorporating climate projections into infrastructure guidelines. These practices can be broadly grouped into four categories:

- **Making Climate Information Actionable.**
  - Regional guidance that incorporates well-established climate projections and associated uncertainty.
  - Climate projections supported with strong confidence from the scientific community, with median and high-end scenarios, are appropriate for infrastructure applications.
- **Developing Guidelines.**
  - Assessing the magnitude of impacts across different levels of projected climate hazards can help pinpoint feasible design criteria.
  - Easily available and standardized data, especially for existing infrastructure, can help practitioners understand future risks.
  - Although it is important to consider a range of future scenarios when developing guidelines, engineers need approved methods and design criteria for incorporating climate change in planning and design. Including both likely and high-end projections in guidelines and clearly explaining when each projection should be used in infrastructure design can facilitate implementation by engineers.
  - Prioritizing practitioner needs and the intended application purposes throughout the development of planning and design guidance can help ensure that guidelines are as useful as possible and increase adoption by infrastructure operators and managers.
- **Implementing Guidelines.**
  - From developing infrastructure guidance to implementing it, inclusive, accessible, and sustained community engagement with a diverse group of stakeholders can help advance equity and ensure guidelines and risk reduction strategies are tailored to the community to which they apply.

    - When developing and implementing guidelines, considering multiple climate hazards and local stressors that could create cascading impacts can help ensure a comprehensive risk management approach.
    - Effective communication of scientific concepts, easily accessible tools, and training materials focused on using climate-resilient design guidelines promote the adoption of guidelines by infrastructure operators and managers.
    - Increased collaboration can help more effectively address climate risks and incorporate resilience in infrastructure planning.
- **Educating Decision-Makers.**
    - Establishing shared understanding and a working knowledge base and terminology with decision makers can help facilitate intra- and inter-agency coordination.

The leading practices identified in the workshop series highlight the extensive work happening across the U.S. to advance climate resilience through infrastructure design and community planning. Many communities across the United States are, in some way, exploring how to incorporate climate science into infrastructure planning or design. This reflects the increasingly widespread understanding that climate change is a pressing problem, and science-informed, local resilience measures are important for mitigating risks associated with climate change in different regions. There remains much work to be done to support communities that are working to incorporate climate projections into infrastructure guidelines. The findings from the workshops will inform the next update to NIST's Community Resilience Planning Guide (CRPG) to better support resilience planning in US communities.

1. Introduction & Background

Weather- and climate-related disasters are on the rise, and their impacts are often greatest in underserved communities (Jay et al., 2023). These impacts are expected to worsen unless guidance is available for infrastructure improvements that address future climate risks. To address this challenge, the National Institute for Standards and Technology (NIST), National Oceanic and Atmospheric Administration (NOAA), and American Society of Civil Engineers (ASCE) are working to advance community resilience[1] planning and assessment in the built environment.

NIST and ASCE both play a critical role in developing and promoting the use of engineering standards and practices. The NIST Community Resilience Planning Guide (CRPG) for Buildings and Infrastructure Systems (2015) and the companion Playbook (2020) support resilience planning in U.S. communities (e.g., municipalities, counties, community organizations). As part of community resilience planning, the CRPG focuses on key infrastructure systems (e.g., buildings and structures, water, energy, transportation, communication) and how they support critical functions for a community in the wake of disaster and forms the basis for other NIST-developed tools and methods. ASCE standards and manuals reach thousands of engineers across the world. NIST, NOAA, and ASCE recognize that use of climate science to make infrastructure more resilient requires stronger collaboration between civil engineering and climate science (Parris, Heitsch, and Carlson 2023). Similarly, NOAA plays a vital role in developing and promoting the use of sound climate science, including understanding and applying relevant projections[2] of future climate conditions.

In January 2021, NIST convened a virtual workshop on incorporating climate change data in United States building codes and standards. Attendees included experts from the climate science community and the building codes and standards community. The goal of the workshop was to discuss the climate data needs for building codes and standards and to ensure that the climate science community understands the specific needs of the building codes and standards community. A subsequent collaboration between NIST, NOAA, and ASCE began in November 2021 with the goal of accelerating the development of climate-resilient infrastructure guidelines.

In early 2023, ASCE and NOAA began a formal partnership, holding a series of workshops on climate science needed to inform civil engineering design followed by a one-day Leadership Summit. The summit brought together scientists, civil engineers, planners, and infrastructure managers to discuss how best to support civil engineers in designing climate-resilient and sustainable infrastructure. One theme from the discussion was the importance of supporting

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[1] NIST defines 'resilience' as: "the ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions." Resilience is an umbrella concept that includes planning, design, adaptation, and mitigation to withstand hazard events, as well as response and recovery to restore functions.

[2] For the purposes of this report, the IPCC definition of 'projections' is used: "A projection is generally regarded as any description of the future and the pathway leading to it. However, here we define a projection as a model-derived estimate of future conditions related to one element of an integrated system (e.g., an emission, a climate, or an economic growth projection). Projections are generally less comprehensive than scenarios, even if the projected element is influenced by other elements. In addition, projections may be probabilistic, while scenarios do not ascribe likelihoods." (Carter et al. 2007).

revisions of ASCE standards, like ASCE-7 (Minimum Design Loads and Associated Criteria for Buildings and Other Structures) which is currently developing a new non-mandatory chapter to address future climate conditions for ASCE 7-28. Another key finding from the workshop is that the use of climate data in infrastructure design largely remains ad-hoc (Parris, Heitsch, and Carlson, 2023).

Building on the previous workshops, NIST, NOAA, and ASCE partnered to convene three workshops focused on sea level rise and coastal storms, inland flooding and urban planning, and wildfire to identify ways that communities are incorporating climate science into infrastructure design. The workshop series and this report will inform the next update to the CRPG. This report provides a summary of the workshop series, including content presented in each workshop and general findings/themes from across the three workshops. The report is organized as follows:

1. Introduction and Background describes the purpose and context of NIST, NOAA, and ASCE's partnership and the workshop series.
2. Workshop Context provides an overview of the workshop objectives and describes how case studies were selected for the workshops.
3. Key Practice Considerations for Using Climate Science summarizes key climate science elements relevant to this report.
4. Presentations and Case Studies summarizes the presentations and case studies from each of the three workshops.
5. Cross-cutting Leading Practices and Gaps synthesizes the leading practices and gaps identified across the workshops.
6. Summary and Next Steps summarizes the main findings from the workshop series and describes next steps for NIST, NOAA, and ASCE.
7. Appendices are included for each of the workshops providing additional context and detail on discussions from the workshops.

2. Workshop Context

Numerous climate hazards impact a wide variety of sectors in diverse regions of the United States (Jay et al., 2023). NIST, NOAA, and ASCE recognize that three workshops are insufficient to explore all relevant sectors and regions, or combinations thereof. Owing to this complexity, NIST, NOAA, and ASCE developed and refined objectives and case study criteria for the workshop series to allow for comparative analysis. This section describes the workshop objectives and criteria for the case studies.

Objective 1: Explore case studies of leading practices for identifying, selecting, and utilizing climate change projections in infrastructure planning and design. In the absence of standards, 'leading practices' refers to local or regional practices that have proven effective in individual settings but still require continued application to determine efficacy as a standard or best practice.

Objective 2: Document transferable lessons for using climate information. As noted in the United States' recent fifth National Climate Assessment (NCA 5), there is wide agreement that interaction between scientists and decision-makers makes climate science and information more usable and actionable (Wasley et al 2023). Government officials, community members, and individual homeowners can all be decision-makers. However, in the case of these workshops, the focus was primarily on infrastructure practitioners and professionals involved in applying climate projections to infrastructure design. Participation by planners, infrastructure designers and engineers, interdisciplinary climate scientists, and officials with oversight of infrastructure systems was sought.

Workshops were primarily geared toward infrastructure practitioners and professionals, informally defined as those involved in applying climate projections to infrastructure design. Workshops were attended by designers, engineers, interdisciplinary climate scientists, and official with oversight of infrastructure systems.

Objective 3: Connect infrastructure planning to justice and equity issues where feasible. Infrastructure design, planning and implementation has historically limited or excluded community participation, especially in places burdened by disinvestment and systemic bias (Parris, Heitsch, and Carlson, 2023). While the CRPG emphasizes the importance of collaboration and engagement in community resilience planning, equity in infrastructure design and engineering warrants a dedicated effort to consider stronger participation in infrastructure decision-making (procedural equity), accounting of the distribution of infrastructure services (distributive equity), and historic burdens and lived experience of communities impacted by aging and declining infrastructure (contextual equity). Given the focus on climate projections, the workshops sought to frame questions and surface important equity-related issues that could be advanced in future dialogues with a broader set of participants.

Based on these three objectives, a set of criteria was developed to better facilitate comparison of practices across diverse contexts (see Table 1). The criteria were generally considered guiding principles. No single case study meets all criteria. For example, as noted above, while more case studies on equitable community resilience planning are emerging, there were few examples specifically related to the highly technical process of applying climate projections into infrastructure design and implementation, a gap confirmed by workshop participants in the results described below (see Section 5).

Table 1. Case Study Selection Criteria

Criteria	**The case study…**
Published plan or guidance	…has a published plan or design guidance that incorporates climate projections into infrastructure design. Publication of the plan or guidance supports traceability to ensure this work builds on documented practices.
Focus hazard[3]	…directly addresses one or more of the hazards selected as focal points for the workshops – sea level rise and coastal surge, extreme rainfall and inland flooding, and wildfire. Multi-hazard mitigation and planning is increasingly identified as a leading practice for strengthening community resilience (see Section 5). It is, however, considered to be an emerging practice and consequently this workshop series focused only on individual hazards.
Communities and equity	…illustrates equity principles in the process of developing the plan or guidance or in the final product. As noted in the description of the objectives, there are limited case studies that fit this and all other criteria.
Recent extreme events	…is in a location that has recently experienced extreme events related to the focus hazard covered. More emphasis is emerging on proactive and/or anticipatory actions to build resilience to climate impacts. However, prior to the historic investments of the Inflation Reduction Act (IRA), the Infrastructure and Investment Jobs Act (IIJA), and Bipartisan Infrastructure Law (BIL) and the initiation of the Federal Emergency Management Administration's (FEMA) Building Resilient Infrastructure and Communities (BRIC) program, infrastructure improvements were largely funded in the wake of extreme events. In identifying areas impacted by extreme events, the aim was to find case studies that might be implementing resilient infrastructure improvements, to better understand how the application of climate projections carried through to that phase.
Recent trends	…is in a location where the focus hazard is worsening.

In addition to these case study criteria, regional diversity and population density were considered to ensure that the selected case studies represented a diversity of regions and location types (e.g., both large, densely populated cities and more rural areas).

Workshop participants included: planners, infrastructure designers and engineers, interdisciplinary climate scientists, and officials with oversight of infrastructure systems. Each

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[3] Specific climate hazards chosen for the workshops were sea level rise and coastal surge, extreme rainfall, and wildfire.

workshop included a plenary session to provide context on the objectives of the workshop series, the criteria for the case studies, and the CRPG. A plenary panel then included presentations with the state of science related to the focus hazard and three case study presentations to illustrate local approaches to developing and applying design guidelines that incorporate climate projections. The workshops included discussion groups to explore leading practices from participant experience beyond the case studies. Participants split into three or four discussion groups at each workshop, and each group included at least one practitioner from each of the case study regions to help relate the experience of participants back to the presented case studies. More detail on the agenda and process for each workshop can be found on the NIST 2023 Climate Planning for Community Resilience Workshops webpage.

3. Key Practice Considerations for Using Climate Science

The design life of infrastructure spans multiple decades, and engineers and designers choose performance targets based on design requirements and expected hazards. As such, practitioners need information regarding future climate conditions in order to design resilient infrastructure. Currently, there are few building or infrastructure codes that require performance targets to be set to accommodate future conditions. For example, design flood elevations dictate how high roads, buildings, or levees must be to avoid flooding during a given storm, which partly depends on what sea level may be in the future.

In order to estimate future conditions, scientists use climate projections, which are simulated climate responses to different scenarios of societal change (population, land use, etc.) and concentrations of greenhouse gases (GHGs). Climate projections are based on numerical models, referred to as Global Climate Models (GCMs), that help simulate the earth and climate system. As illustrated in the case studies below, many leading practices in resilient infrastructure and design involve choices over which climate projection data to use. Making those choices involves both interpreting some of the foundational assumptions and inherent limitations or uncertainty in climate models and weighing the important tradeoffs of using certain projections, such as cost. This section addresses the main challenges that many practitioners face when selecting and using climate projects for infrastructure design.[4]

Using an Ensemble (or Group) of Climate Models Versus One Model

Infrastructure practitioners must choose which climate models to use. Many different climate models exist at different labs and research centers across the world. Some climate models focus more on ocean processes and other models focus more on feedback processes between the atmosphere and land surface, or other processes. In this regard, each climate model simulation can be thought of as a different experiment where the data and assumptions provide valuable information about how the earth system responds to different disturbances. The Coupled Model Intercomparison Project (CMIP) coordinates climate modeling efforts across the world to ensure that models meet performance benchmarks (e.g., in reproducing historical climate) and address a

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[4] More information on climate projections can be found in Appendix 3 of the Fifth US National Climate Assessment (NCA5).

set of standardized experiments. Through CMIP, scientists collaborate and evaluate what is learned from experiments represented by climate models. CMIP – Phase 6 (CMIP 6) represents the latest generation of climate model simulations and now includes results from many models (e.g., from at least 36 models).

Over the past decade, scientists and infrastructure practitioners have increasingly gravitated toward using an ensemble of model results as opposed to relying on the results of just one or a few climate models. Using an ensemble offers at least two distinct advantages.

First, individual climate models have inherent biases and uncertainties, and using an ensemble of model results helps limit those biases. The biases and uncertainties in individual climate models are associated with a range of factors, including unpredictable natural variability, model-specific parameterizations, and different model sensitivities to greenhouse gas concentrations. Using results from an ensemble of climate models cannot completely eliminate those biases, and there is still uncertainty (or error bars) associated with the results. However, using an ensemble helps limit those biases by essentially representing all the simulations of earth processes together (Semenov and Stratonovitch 2010; Frankcombe et al. 2015).

Second, using an ensemble of model results can improve understanding of future risks by allowing practitioners to calculate a probability distribution function (PDF) from the larger set of results from a model ensemble. Importantly, climate projections are not predictions or forecasts. Nevertheless, probabilities from an ensemble of climate models help practitioners interpret the odds that the earth system will respond to specific perturbations. When considering potential climate risks in the future, communicating the likelihood of different levels of risk facilitates better communication about the tradeoffs between choosing different design conditions. Probabilities calculated from the models indicate, for a given scenario of societal change and associated amount of climate warming, the likelihood that the earth system will respond in a certain way.

Safeguarding Against a Warming World

Infrastructure practitioners have to weigh the tradeoffs of safeguarding against climate changes due to higher levels of warming and feasibility factors such as cost. To develop climate projections, scientists need to make assumptions about societal change and how that will affect future concentrations of greenhouse gases (GHGs) in the atmosphere and oceans. These assumptions are captured in different climate scenarios[5], which are essentially plausible pathways of future change developed through data and expert opinion. CMIP relies on two coordinated sets of scenarios called Shared Socioeconomic Pathways (SSPs) and Representative

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[5] NCA5 defines scenarios as: “A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts but are used to provide a view of the implications of developments and actions.”

Concentration Pathways (RCPs)[6]. These scenarios drive the climate model simulations described above.

SSPs describe alternative futures of socioeconomic development based, for example, on different forms of energy and land use, consumption, agriculture, and governance. SSPs are narrative formulations that help account for the uncertainty surrounding individual and collective human choices. RCPs provide scenarios for emissions and concentrations of GHGs, aerosols, and chemically active gases that can be associated with the alternative futures represented by SSPs.

When choosing which climate projections to use, infrastructure practitioners have to consider how much global warming to anticipate. Many of the case studies illustrated below use variations of SSP-RCP combinations 2-4.5 and 5-8.5. SSP2-RCP4.5 (labeled SSP2-4.5) is an intermediate scenario reflecting a ~50% reduction of carbon dioxide (CO_2) emissions from the year 2000 through the use of low-carbon technology and renewable energy (USGCRP 2023). SSP5-RCP 8.5 (labeled SSP5-8.5) is a very high scenario reflecting quadruple the amount of CO_2 emissions from levels in the year 2000, high population growth, and continued fossil fuel development (USGCRP 2023). Both levels of warming (higher and lower) result in some amount of risk to society.

For example, if society increases its use of fossil fuels, then GCMs will project greater future sea level rise under a higher future emissions pathway (e.g. SSP5-RCP 8.5). This scenario may lead scientists, designers, engineers, and public officials to consider higher flood elevations (i.e. more stringent design conditions). However, more stringent design conditions often come with higher construction costs. If society reduces its use of fossil fuels, then models will project less sea level rise under a lower emissions pathway (e.g. SSP2-RCP 4.5). This scenario may lead scientists, designers, engineers, and public officials to consider lower flood elevations (i.e. less stringent design conditions) often with lower construction costs. Each of these scenarios also have long-term costs and benefits that should be considered as part of the evaluation. For example, increased initial project costs may result in reduced future damages and losses. The tradeoffs are a matter of risk tolerance for a given project or asset(s) relative to which scenario(s) of the future are considered to be more or less likely. As illustrated in the case studies below, infrastructure practitioners often perform formal and informal sensitivity analyses to consider safeguarding against the risks of these two warmer worlds on one hand, and the feasibility of building to the higher scenarios (cost, politics, etc.) on the other hand.

Downscaling Climate Models to Infrastructure Location and Service Area

Infrastructure practitioners rely on ‘downscaled’ climate projections to develop data more specific to the location of their asset or service territory as specific as an individual building, block, or parcel of land. GCMs divide the Earth into grid cells to perform simulations of future climate. These cells range in size from approximately 100 – 600 square kilometers (roughly 39 – 231 square miles). While the resolution of GCMs has significantly improved with advances in

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[6] For more background on the co-development of RCPs and SSPs, see: Moss, R., Edmonds, J., Hibbard, K. et al. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756 (2010). https://doi.org/10.1038/nature08823.

technology, small variations in climate data can result in large impacts on cost or feasibility of proposed adaptation projects. For example, in some heavily urbanized areas, a three-inch difference in pipe size to accommodate higher projected rainfall can double the cost of stormwater improvements, rendering them cost prohibitive (Cook et al. 2020). Consequently, practitioners seek higher spatial resolution climate data to better assess risk and vulnerability and to fine-tune designs. To address this problem, climate scientists offer downscaled climate projections using two primary techniques.

Climate scientists use statistical or dynamical downscaling to produce higher spatial resolution climate data. Statistical downscaling uses statistical relationships between large-scale climate patterns from GCMs and local climate observations. Dynamical downscaling relies on high-resolution regional simulations using weather forecasting or similar models to represent the effects of large-scale climate processes at regional or local scales of interest. Both techniques result in finer-resolution climate data, roughly a few kilometer (or a few square mile) grid cells. While dynamical downscaling better resolves regional to local climate variations, it is more computationally intensive. Therefore, statistical downscaling is more commonly used. As illustrated in the cases below, there are different methods of statistical downscaling (e.g. delta method vs. quantile mapping).

While both dynamical and statistical downscaling offer climate data tailored to a region or location, there is still uncertainty associated with the local climate projections each method provides. For example, while models project that conditions may be conducive to more intense rainfall in the future, they cannot predict the exact location, timing, or magnitude of intense thunderstorms or other rain-producing events. For this reason, practitioners use scenario planning, robust decision-making, adaptation pathways, and other risk-based decision-making frameworks that address multiple possible futures in the planning stage. These frameworks are useful in the planning and design phase of infrastructure projects to arrive at specific performance targets after evaluating the tradeoffs across a range of potential future conditions.

Comparing Change Over Time

Because climate projections are not predictions, infrastructure practitioners are faced with choosing which time horizons to use for planning purposes (Carter et al. 2007). GCM outputs typically extend to the year 2100. However, scientists often calculate ‘timeslices’ where they average results over a 10-to-30-year period centered on the desired timeframe to minimize the influence of interannual climate variance (e.g., the impact of an El Nino event on temperature anomalies). For example, to consider future conditions at mid-century, scientists typically report results as “2050s” using model data from 2041 – 2060. The results for the 2050s would be compared to a baseline for present day conditions. Baselines are typically derived from average, observed conditions over a similar 20-to-30-year period to align with climate normal calculated by NOAA. Climate normals are calculated over 30-year periods to allow for variability caused by natural climate patterns like the El Nino Southern Oscillation and the Pacific Decadal Oscillation, which fluctuate over regular periods of time ranging from a couple of years to multiple decades.

4. Presentations and Case Studies

This section summarizes the presentations and case studies from the workshop series. Each workshop included one general presentation to provide an overview of the science and/or state of practice for the focus hazard. Additionally, each workshop featured three case studies of incorporating climate projections to advance infrastructure resilience. In addition to providing an overview of each of the presentations and case studies, this section also offers a comparison of the three hazard case studies with a focus on leading practices. See the NIST website for recordings of the workshop presentations and case studies.

4.1. Workshop 1: Sea Level Rise and Coastal Storm Surge

Sea level rise is a slow-onset hazard that is generally easier to project than extreme rain events and wildfires, which are more complex, rapid-onset events that are influenced by multiple factors. As such, sea level rise has the most mature body of science compared to other weather and climate extremes and has a more robust history of being used to inform infrastructure guidelines. Practitioners often use sea level rise projections based on GCM outputs corrected for local and regional factors that influence water levels at the coast. For example, many areas in the northeastern United States experience subsidence, or sinking, of the land surface, which results in higher values and rates of projected sea level rise.

Most sea level rise design guidelines provide a framework to support practitioners in selecting the appropriate flood elevation to design at a specific project site, including appropriate sea level rise projections and integrating sea level rise and flood model information. There are many other tools or resources to support practitioners tackling projects in areas that are vulnerable to sea level rise.

4.1.1. Presentation: A Global Survey of Sea Level Rise Projections for Coastal Adaptation

There is no global standard for incorporating sea level rise projections in planning (Hirschfeld et al., 2023). However, based on a global, multilingual survey of two-hundred and fifty-three coastal practitioners, many practitioners (72%) indicate that they have some form of sea level rise planning or guidance for their jurisdiction. While fewer (26%) indicate that they are in the process of developing plans or guidance materials to incorporate sea level projections into planning. Of the respondents that have sea level rise guidance, more than half of them (53%) use a single projection, 14% use both low and high projections, 20% use low, intermediate, and high projections, and 13% use low, intermediate, high, and high-end or extreme (H++)[7] projections. Thus, while ensemble projection use is ideal, not all practitioners are currently using this robust approach. These results are skewed toward the global north (Europe, Australia/Oceania, and North America) (Figure 1), which highlights global inequities in access to information and planning resources.

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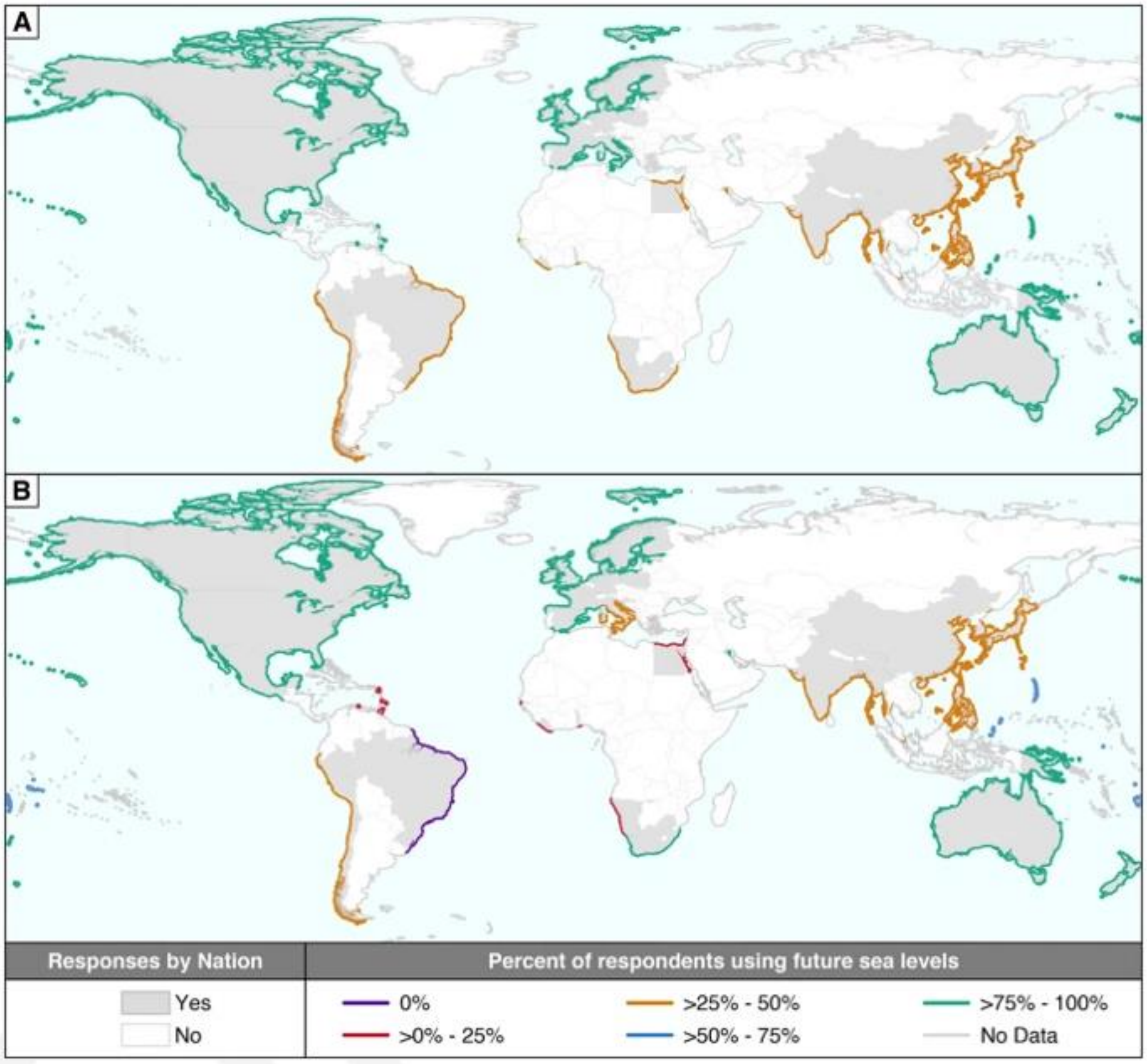
[7] H++ refers to an extreme sea level rise scenario that represents the rapid loss of the West Antarctic ice sheet. This scenario is not recommended for most planning purposes, as the future rate of Antarctic ice sheet loss is highly uncertain and research on this topic is ongoing.

Figure 1. Percent of respondents by continent (A) and coastal region (B) using sea level rise projections in coastal planning. Source: Hirschfeld et al. 2023.



In addition to the global survey, a global committee of practitioners, scientists, and boundary leaders hosted a series of workshops to better understand challenges and gaps in implementation (Hirschfeld et al. 2024). One of the major findings from these workshops was that producing future climate projections at a regional or local scale is required to move adaptation work forward. Thus, production of localized information and building of local capacity are currently high priority needs.

4.1.2. Case Study: New York City, NY

New York City's (NYC) Mayor's Office of Climate and Environmental Justice (MOCEJ)[8] is responsible for preparing NYC for the impacts of climate change with a focus on equity and public health. In service of this task, MOCEJ developed the NYC Climate Resiliency Design Guidelines (MOCEJ Version 4.1 2022). The Guidelines were created to ensure that NYC Capital projects are designed to withstand future climate impacts. The Guidelines are intended to be used in the design process for all new construction and substantial improvements to NYC facilities. Throughout the development of the Guidelines, MOCEJ convened the Design Guidelines Working Group, made up of representatives from more than 15 city agencies. Following the release of a preliminary version of the guidelines in April 2017, internal and external climate design experts extensively reviewed and tested the Guidelines. MOCEJ released revised versions of the Guidelines annually from 2018 to 2020 and updated the guidelines most recently in 2022. In 2021, Local Law 41 mandated a five-year pilot program, under which 20+ City capital agencies apply the Guidelines for the design and construction of dozens of new projects across a wide variety of asset types.

The NYC Guidelines include climate projections for increasing temperatures, increasing precipitation, and sea level rise derived from statistically downscaled projections. Climate projections used to inform the Guidelines were provided by the NYC Panel on Climate Change (NPCC), an independent advisory body that is responsible for synthesizing scientific information on climate change to support policymakers in NYC. The NYC Guidelines average RCPs 4.5 and 8.5 and include information for the 2020s, 2050s, 2070s, and 2100. The likely (middle range) and high-end sea level rise projections used for NYC for 2100 are 22-50 inches (59-127 cm) and 75 inches (190 cm), respectively. The Guidelines recommend using the 50th percentile for SLR projections, and the 90th percentile for heat, with caveats for critical equipment as appropriate.

Throughout the NYC Guidelines, the design life of a capital project informs the selection of the sea level rise projection and design flood elevation for a project. The NYC Guidelines also provide tools and resources for designers to use throughout the resilient design process. These include an exposure screening tool to identify and assess climate change-related hazards, as well as methodologies for conducting a risk assessment and a benefit-cost analysis.

The NYC Guidelines outline four specific steps to assess the risk of tidal inundation and flooding at a project site and determine how to incorporate sea level rise into design flood elevations:

1. Assess tidal inundation due to sea level rise.
2. Address risks in the current floodplain.
3. Address risks in the future floodplain.
4. Identify appropriate design interventions.

The first three steps rely heavily on NYC's Flood Hazard Mapper, an online tool used to assess tidal inundation at a site and to address risks in current and future floodplains. The sea level rise-

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[8] Formerly the NYC's Mayor's Office of Resiliency.

adjusted design flood elevation (DFE) for a project is based on the flood risk information from the tool and the useful life and criticality of the facility. The fourth and final step is to identify appropriate design strategies that meet the project's sea level rise-adjusted DFE (see Figure 2).

For projects exposed to extreme heat, identified by the NYC Heat Vulnerability Index, the Guidelines also include recommendations for future temperature and sizing criteria for HVAC equipment as applicable. For projects exposed to stormwater flooding identified by the NYC Stormwater Flood Maps, the Guidelines include recommendations for stormwater sizing and building level considerations to incorporate future rainfall flooding and intensity.

Once hazard exposure and vulnerability are established, the Guidelines include a list of example design alternatives to consider. This guidance supports city capital project design to consider the climate conditions the project is predicted to experience over its full useful life.

Figure 2. NYC guidelines for determining sea level rise-adjusted DFEs. Source: MOCEJ 2022.

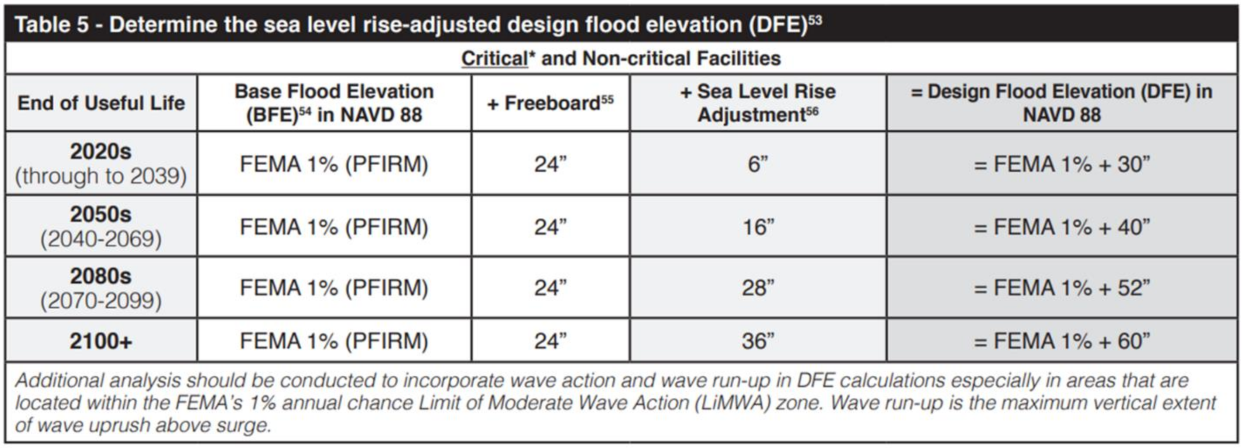


Table 5 - Determine the sea level rise-adjusted design flood elevation (DFE)[53]

Critical* and Non-critical Facilities

End of Useful Life	Base Flood Elevation (BFE)[54] in NAVD 88	+ Freeboard[55]	+ Sea Level Rise Adjustment[56]	= Design Flood Elevation (DFE) in NAVD 88
2020s (through to 2039)	FEMA 1% (PFIRM)	24"	6"	= FEMA 1% + 30"
2050s (2040-2069)	FEMA 1% (PFIRM)	24"	16"	= FEMA 1% + 40"
2080s (2070-2099)	FEMA 1% (PFIRM)	24"	28"	= FEMA 1% + 52"
2100+	FEMA 1% (PFIRM)	24"	36"	= FEMA 1% + 60"

Additional analysis should be conducted to incorporate wave action and wave run-up in DFE calculations especially in areas that are located within the FEMA's 1% annual chance Limit of Moderate Wave Action (LiMWA) zone. Wave run-up is the maximum vertical extent of wave uprush above surge.

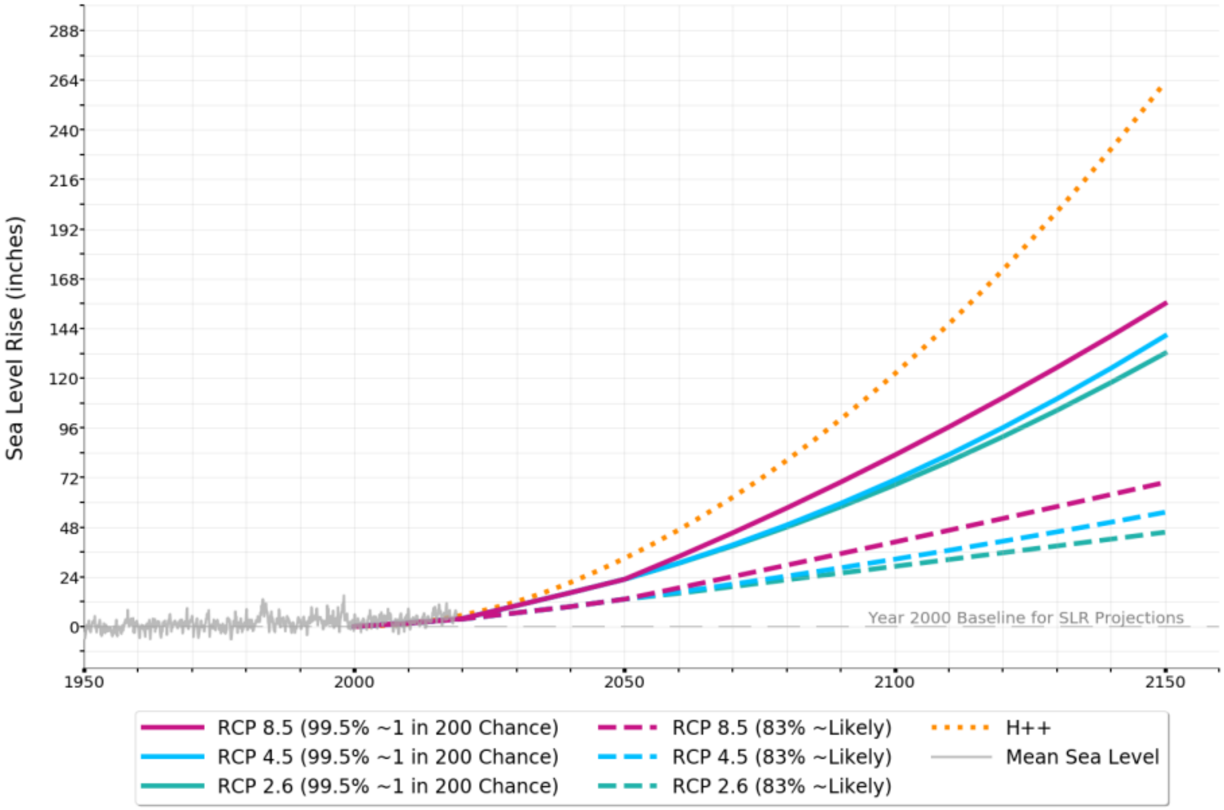
The NYC Guidelines also provide tools and resources for practitioners to use throughout the resilient design process. These include an exposure screening tool to identify and assess climate change-related hazards, as well as methodologies for conducting a risk assessment to identify relevant hazards and a benefit-cost analysis to help guide investments in resilience.

4.1.3. Case Study: San Francisco Bay Area, CA

The City and County of San Francisco's (SF) Capital Planning Committee (CPC) adopted SF's Guidance for Incorporating Sea Level Rise Into Capital Planning (The City and County of San Francisco 2020). CPC makes recommendations to the Mayor and Board of Supervisors on the City's capital expenditures and plans and uses the Guidance when reviewing future Capital Plans to ensure they have adequately addressed sea level rise vulnerabilities and risk. CPC first adopted the SF Guidance in 2014 and updated it in 2015 and 2020 based on implementation experience and revised projections emerging from the State of California including state guidance adopted in 2018 (Ocean Protection Council). The City is preparing to revise its projections again in response to new revised state guidance adopted in 2024.

Although California state guidance recommends using the RCP 8.5 and 2.6 scenarios for planning and design, San Francisco selected RCP 4.5 instead of RCP 2.6 as this future climate pathway is perceived to be a more realistic potential lower bound and reflects current adopted global policies and current trends in energy development. SF's Guidance provides information for 2030, 2050, 2070, 2100, and 2150. SF's Guidance provides the upper end of the likely range (17% chance of being exceeded) and high-end (1-in-200 or 0.5% chance of being exceeded) sea level rise projections recommended by the California state guidance for both RCP 4.5 and 8.5 (Figure 3). The state of California selected the likely value because it represents the upper end of the "likely range," which is defined as one standard deviation around the mean. According to the SF Guidance, "the upper end of the likely range represents a value where sea level rise is more-likely-than-not to fall at or below this value." The state of California selected the 1-in-200 chance value as a reasonable "upper bound" for sea level rise adaptation planning and design. The high-end value used in the SF Guidance for RCP 8.5 is just under 4 m. (13 ft) by 2150.

Figure 1. Relative sea level rise curves used in the San Francisco Guidance. These curves are aligned with the state of California's guidance for sea level rise planning. Source: The City and County of San Francisco 2020.



The SF Guidance outlines four steps to prepare for sea level rise impacts:

1. **Review Science:** Identify sea level rise projections and use sea level rise inundation mapping tools to evaluate potential exposure to future sea level rise and storm surge conditions. Capital project planners are encouraged to consider the design life and location of the asset when selecting a sea level rise scenario.
2. **Assess Vulnerability:** Using the results of Step 1, evaluate exposure, sensitivity, and adaptive capacity to determine if the asset is vulnerable to sea level rise.
3. **Assess Risk:** Evaluate the consequence of an asset failing to determine priorities for adaptation planning.
4. **Plan Adaptation:** Prioritize potential adaptation strategies for vulnerable assets/projects and develop a plan for implementation of specific strategies.

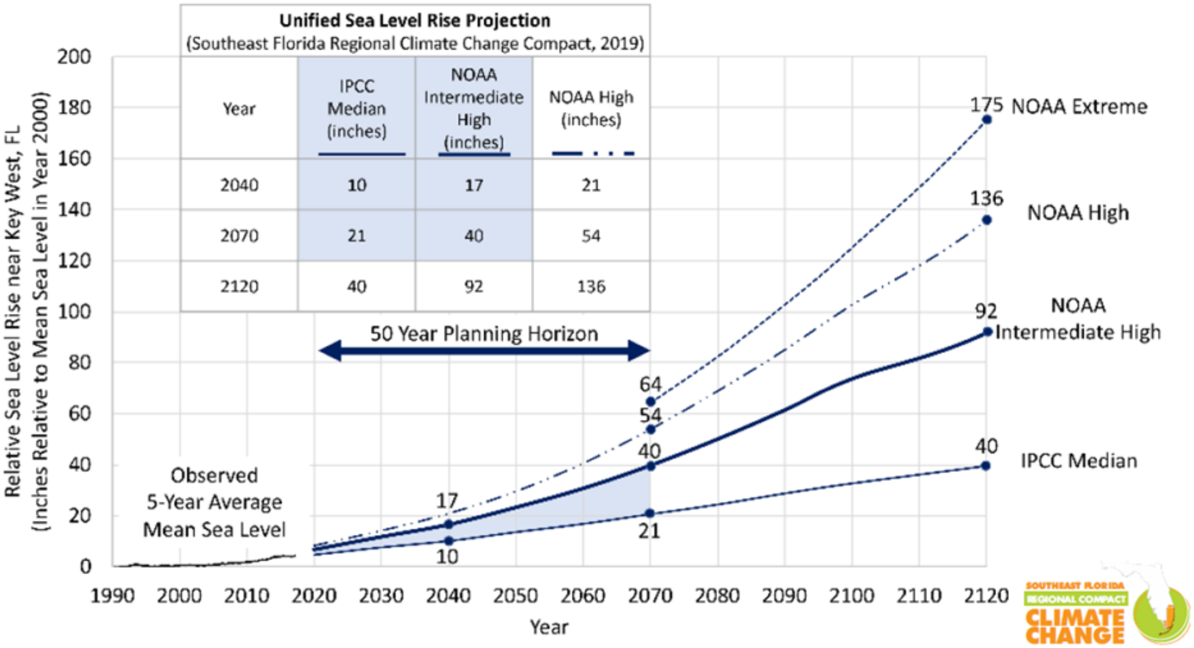
SF developed multiple tools and resources to help planners select which future sea level rise projection to use (Step 1) based on the project location and functional lifespan and assess vulnerability (Step 2). These include SF's sea level rise vulnerability zone map, which can help planners determine if the project site will be inundated under extreme sea level rise plus a 100-year storm event in the year 2100. SF also developed a Sea Level Rise Checklist that must be used alongside the Guidance by capital project managers to evaluate sea level rise vulnerability for the project. The SF guidance also describes how to conduct vulnerability and risk assessments for the site, which can then be used to inform adaptation planning.

4.1.4. Case Study: Southeast Florida

The Southeast Florida Regional Climate Change Compact's Sea Level Rise Ad Hoc Work Group developed the Unified Sea Level Rise Projection for Southeast Florida (Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group 2020). The Work Group, which consists of experts within the academic community and federal agencies, first convened in 2010 to review existing projections and scientific literature and develop a unified sea level rise projection for the region. The goal of developing the projection was to support local governments and regional entities to understand future sea level rise and develop appropriate adaptation strategies, policies, and infrastructure designs. The Compact released the region's initial Guidance in 2011, revised it in 2014, and most recently updated it in 2019. Southeast Florida's Guidance includes the sea level rise projections provided in the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report and in NOAA's 2017 Global and Regional Sea Level Rise Scenarios for the United States.

As shown in Figure 4, Southeast Florida's Guidance provides three main projections for different design applications: the IPCC Median of RCP 8.5, NOAA Intermediate High, and NOAA High (IPCC 2014) (Sweet et al., 2017). The Guidance provides projections for short-term (2040), medium-term (2070), and long-term (2120) timeframes. The high-end projection is 136 inches (345 cm) by 2120. The Guidance recommends the IPCC Median curve be applied to most non-critical, low-risk projects with short design lives (i.e., less than 50 years) that have limited interdependencies with other infrastructure or services. The Guidance recommends the NOAA Intermediate High curve be applied for non-critical infrastructure that will be in service during or after 2070. Finally, the guidance recommends the NOAA High curve for existing and proposed critical, high-risk infrastructure that has a long design life (i.e., greater than 50 years) and is interdependent with other infrastructure or services. In practice, the county governments advocate for application of the NOAA Intermediate High curve with a minimum 50-year planning horizon, which translates to 40 inches of sea level rise relative to 2010 conditions for the year 2070.

Figure 4. Southeast Florida's Unified Sea Level Rise Projection. Source: Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group 2020.



Unified Sea Level Rise Projection
(Southeast Florida Regional Climate Change Compact, 2019)

Year	IPCC Median (inches)	NOAA Intermediate High (inches)	NOAA High (inches)
2040	10	17	21
2070	21	40	54
2120	40	92	136

Although the regional projection integrates the Key West gauge for reference, the Guidance provides instructions for converting the projection values into regional values based on three other gauges in Southeast Florida. Three main tools are recommended in the guidance: the USACE Sea Level Change Curve Calculator, the USACE Sea Level Tracker, and the Florida Sea Level Sketch Planning Tool. Multiple modeling and planning processes incorporate the region's sea level rise projection.

4.1.5. Sea Level Rise Case Study Comparison

All three case study guidelines presented above include both likely and high-end sea level rise projections for multiple time horizons (near-, medium-, and long-term). Both NYC and SF use projections based on RCP 4.5 and 8.5. In the case of NYC, the NPCC developed and provided local projections, whereas SF relied heavily on state-level guidance to determine which projections to use. However, SF's approach diverged slightly from the California state guidance in order to ensure that SF's projections were developed for a more regional scale. For example, although California state guidance recommends using RCP 2.6 as the lower bound for planning and design, SF selected RCP 4.5 instead, as the city determined that it was a more realistic lower bound for their locale. Southeast Florida's Guidance provides three different projections, all of which correspond to high emissions scenarios. The IPCC Median projection uses RCP 8.5, whereas the NOAA Intermediate High and the NOAA High projections roughly correspond to SSP3-RCP-7.0 or SSP5-RCP-8.5 (Sweet et al 2022, Figure 2.7). NYC and SF both incorporated local/regional projections in their guidelines, whereas Southeast Florida used global projections that were adapted for regional applications. These examples illustrate different options for choosing which sea level rise scenarios to apply at the regional level.

All three case study guidelines include design life, criticality, and investment level as key considerations for selecting which sea level rise projections and SSP-RCP scenarios to use when designing a project. However, each set of guidelines recommends a slightly different approach to incorporating sea level rise into project design. The NYC guidelines include step-by-step instructions for calculating future sea level rise-adjusted base flood elevations. The SF guidelines encourage a more detailed vulnerability assessment before prioritizing adaptation strategies, and the Southeast Florida guidelines do not provide detailed design instructions but describe when each of the three projections should be used.

4.2. Workshop 2: Rain and Inland Urban Flooding

Hydraulic engineers rely on precipitation frequency estimates, often in the form of intensity-duration-frequency (IDF) curves, to design stormwater infrastructure.[9] Many practitioners currently use IDF curves from NOAA Atlas 14, the authoritative atlas of precipitation frequency estimates for the United States. IDF curves are based on historical rainfall data and do not incorporate future climate projections. However, given that trends in precipitation frequency and severity are diverging from historical patterns, practitioners increasingly need future-adjusted IDF curves that incorporate climate projections in order to ensure that current stormwater infrastructure can withstand future precipitation events. NOAA is currently in the process of developing NOAA Atlas 15, which will be presented in two volumes (Figure 5). Volume 1 will account for temporal trends in historical observations, and Volume 2 will use future climate model projections to generate adjustment factors for the historical observations presented in Volume 1.

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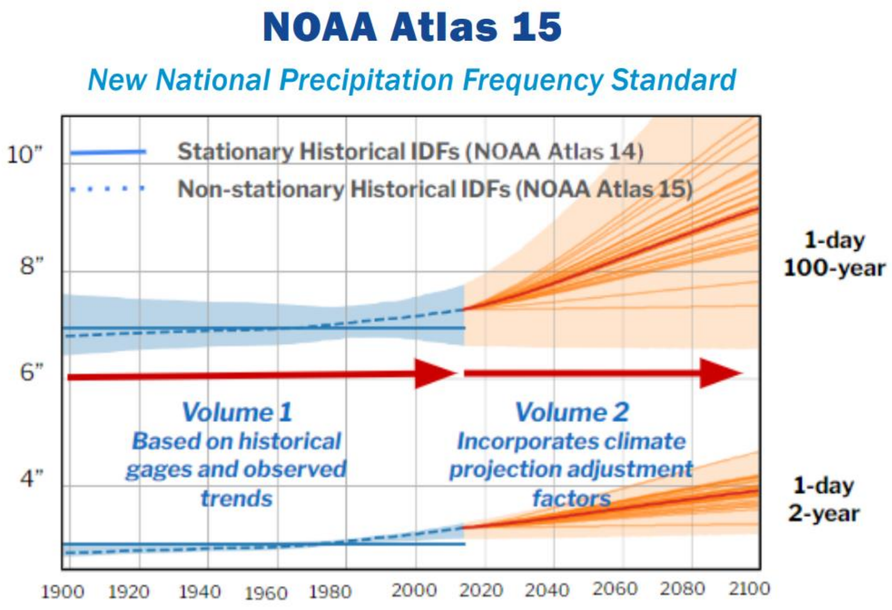
[9] Precipitation frequency estimates are defined as the precipitation depth at a particular location, for a given storm duration, that has a statistically-expected1-in-YY chance of being exceeded in any given year, where YY is the statistical annual recurrence interval.

Figure 5. Overview of NOAA Atlas 15. Source: NOAA.



Although NOAA Atlas 15 will be a critical resource for hydraulic engineers across the U.S., the final product is not expected to be available until 2027. In order to address the current and pressing need for future-adjusted IDF curves, many practitioners have begun using interim approaches for developing future precipitation projections. For example, some practitioners apply a change factor to current IDF curves from NOAA or regional sources. Others assume a consistent percent increase in precipitation estimates based on projections for their regions. The case studies below highlight examples of different approaches that can be used to develop future precipitation projections.

4.2.1. Presentation: Developing and Providing Heavy Rainfall Projections

The NOAA Mid-Atlantic Regional Integrated Sciences and Assessments (MARISA) (now known as CAP/RISA) team developed future projected IDF curves for both the Chesapeake Bay Watershed and the Commonwealth of Virginia through substantial co-production with users and stakeholders (Miro et al., 2021). This was a cross-institutional research effort supported by researchers from Carnegie Mellon University (CMU) and the Northeast Regional Climate Center NRCC) at Cornell University. The development team incorporated two downscaling methods (one statistical and one dynamical) and two emissions pathways (RCP 4.5 and RCP 8.5) into the IDF curves.[10] They developed change factors (i.e., the projected future precipitation divided by the historical precipitation for a given location) associated with rainfall intensity and duration to

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[10] For more background on Representative Concentration Pathways (RCPs), see Moss, R., Edmonds, J., Hibbard, K. et al. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756 (2010). https://doi.org/10.1038/nature08823.

account for climate model bias and to easily apply to NOAA Atlas 14 data to develop future-adjusted IDF curves.

Miro et al. (2021) emphasize the importance of developing results that are usable, transparent, and adaptable. Interactive websites with clear data visualizations increase usability. Examples of helpful interactive websites include the New Jersey Extreme Precipitation Projection Tool and the Projected Intensity-Duration-Frequency Curve Data Tool for the Chesapeake Bay Watershed and Virginia. Documentation of methods, data sources, and uncertainty are essential to improve transparency. Additionally, developing products that can be used in conjunction with Atlas 14 makes updates easier.[11]

4.2.2. Case Study: Boulder County, CO

Following a devastating flood in 2013, Boulder County, CO received a FEMA Pre-Disaster Mitigation Advanced Assistance grant to create a transportation system resilience study and action plan that examined: 1) vulnerabilities to the system from climate-related hazards, 2) characteristics of the potential impacts (e.g., duration, populations affected), 3) possible actions to improve resilience, and 4) the costs to take actions to mitigate impacts. The development of Boulder County's Floodplain Management and Transportation System Resiliency Study and Action Plan involved significant public and stakeholder input gathered through an extensive engagement process. Throughout the study process, a multidisciplinary Steering Committee comprising representatives from different Boulder County departments and other stakeholders advised on key decisions and helped provide solutions. As part of the resilience study, Boulder County assessed varying guideline proposals (e.g., designing to 100- and 500-year elevations for new bridges) and ultimately recommended a design guideline at the end of the study.

Boulder County applied the City Simulator tool to incorporate projected future climate impacts into the resilience study. City Simulator first creates a digital twin of the region of interest. A Monte Carlo simulation is then conducted via a nested loop algorithm to understand potential impacts due to, or exacerbated by, climate change. City Simulator uses statistically downscaled climate models for daily rainfall data. Downscaled projections are coupled with riverine and pluvial[12] flood models to simulate a variety of flooding scenarios. The City Simulator then applies flooding levels to determine which buildings and infrastructure are impacted and estimates how much damage may occur to impacted infrastructure and its recovery time.

The City Simulator methodology incorporates a base scenario that accounts for resilience actions already in place, such as banning new construction in the regulatory floodway and requiring specific design elevations. City Simulator therefore provides a comparative framework to evaluate alternative resilience actions against present day conditions. City Simulator also

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[11] See the technical report on developing IDF curves for the Chesapeake Bay Watershed and Virginia for an example.

[12] 'Pluvial' describes an extreme rainfall event. Pluvial flooding occurs when extreme rainfall creates a flood independent of existing water bodies. In other words, the flood is caused by the rainfall itself, rather than a lake, stream, or river overflowing its banks (Resources for the Future).

incorporates a variety of metrics to estimate the full cost of a flood event, including building recovery days, disrupted trips, lost production, and direct damage to buildings.

Boulder County conducted a multi-decadal simulation (2019-2050) of future flood events and identified the top 10 most vulnerable bridge and culvert locations in the County, along with projected impacts. They estimated that $206 million worth of transportation assets are at risk of flooding. These findings informed the identification and prioritization of resiliency actions in addition to helping provide justification for future resilience investments.

4.2.3. Case Study: Philadelphia, PA

2022 Guidance and Approach

The Philadelphia Water Department (PWD) established its Climate Change Adaptation Program (CCAP) in 2014 to characterize climate-related risks, identify adaptation strategies, and advance implementation of strategies to reduce risk. After first identifying priority planning needs, the program focused its efforts on developing actionable science (defined as "data, analyses, projections, or tools that can support decisions related to managing climate risks and impacts") that is customized for the department's infrastructure needs (USGS, n.d.).

In creating an actionable precipitation product, PWD first compared daily precipitation output from climate models with local rain gauge data and found that daily mean precipitation for 1995-2015 was underestimated in the climate models. In addition, the daily precipitation output from the GCMs do not have sufficient resolution for urban wastewater and stormwater applications, which require hourly and sub-hourly data. Based on these findings, PWD used delta change factors to create a future hourly time series rather than downscaling daily climate model output (Maimone et al., 2019). PWD calculated change factors based on season and storm size for a climate model ensemble average of daily precipitation output from 1995-2015 and 2080-2100. The delta change factors were applied to historical hourly precipitation data from a local rain gauge to derive a future daily precipitation time series.

A key assumption underlying PWD's approach is that **only the intensity, not the frequency or duration,** of precipitation events is projected to increase in Philadelphia, as indicated by climate projections. This assumption allowed PWD to develop an approach based on the current frequency and duration of storms and dry spells in Philadelphia. The products developed from this analysis include future rainfall times series for use in PWD's hydrologic and hydraulic models, future IDF and Depth-Duration-Frequency (DDF) curves for use in infrastructure design, and a stochastic weather generator that allows exploration of future variability in rainfall intensity and frequency.

PWD integrated these actionable precipitation products into design, planning, and operations practices. To do this, PWD developed their Climate-Resilient Planning and Design Guidance, which is intended to be readily used by planners and engineers. PWD leadership supported a department-wide policy requiring the use of the Guidance, which was implemented in 2022. Now all PWD projects use these guidelines to the extent feasible from planning through construction. Although PWD's Guidance does not provide specific instructions for applying adjusted IDF statistics to projects, it does include examples of applications in an appendix. The Guidance is intended to be a living document; any future updated analyses will be incorporated.

New Extreme Precipitation Analysis

PWD is currently working on version 1.1 of their Guidance, which will include findings from their most recent extreme precipitation analysis. The recent analysis compares three techniques for using climate models to estimate change factors for future precipitation (Maimone et al. 2023). The first method uses precipitation data, specifically the top 20 daily rainfall values from climate models. The other two methods use temperature data from climate models combined with an empirical relationship (Clausius-Clapeyron[13]) derived from observed data. The first of these two empirically-based methods is based on a 7% increase in precipitation for every 1°C of warming, and the second of the empirically-based methods uses a 7-12% increase in precipitation for every 1°C of warming. For all three models, PWD generated temperature change factors on a decadal basis, using a reference period from 1986 to 2005, and used sub-hourly rainfall depths based on ratios between hourly and sub-hourly rainfall observations provided by NOAA.

Due to PWD's low risk tolerance, the climate model outputs were based on a high emission pathway (RCP 8.5). Table 2 compares the projected changes in precipitation for 24-hour storm events across the three methods used. The analysis indicates that the method using precipitation data from climate models is likely to underestimate future extreme rain events because it is based solely on climate model output, which tends to underestimate extreme storm events for specific locations. Additionally, this method is sensitive to the number of climate models used in an ensemble, as well as the period from which the storms are selected. Both of the temperature-based models represent the higher end of extreme storm intensification estimates and are only slightly higher than estimates from other precipitation products, such as the U.S. Department of Defense Strategic Environmental Research and Development Program (SERDP) IDF curves and MARISA IDF curves for the Chesapeake Bay Watershed (Miro et al., 2021).

Table 2. Comparison of Projected Changes in Precipitation for 24-Hour Storm Events under RCP8.5

Model	2050s	2080s
Low (20-storm method)	10%	18%
Medium (Clausius-Clapeyron)	23%	35%
High (super Clausius-Clapeyron)	25-33%	38-50%

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[13] The Clausius-Clapeyron relationships are used in thermodynamics to describe the temperature dependence of vapor pressure of a liquid. As temperature increases, atmospheric water vapor content enhances. These relationships, therefore, can be used to understand how precipitation may change with a warming climate.

4.2.4. Case Study: Southeast Michigan

The Southeast Michigan Council of Governments (SEMCOG) developed downscaled precipitation projections to analyze how future climate changes may affect the organization's transportation and stormwater operations and planning. The goal of SEMCOG's analysis was to assess the relative change in impacts due to climate change rather than finding the best prediction of future climate, given the inherent uncertainties. The analysis utilized NOAA Atlas 14 precipitation frequency estimates as a baseline for adjustments since some values do not cover the entire historical record up to the present day. For instance, data values are not continuously updated and do not always account for recent extreme weather events. Thus, SEMCOG adjusted their design guidance to better reflect recent trends in precipitation extremes.

For Southeast Michigan, Tetra Tech developed future IDF curves using a set of dynamically downscaled climate models that better simulated regional climate, specifically lake effects (Notaro, Bennington, and Vavrus 2015). SEMCOG then performed additional bias correction using equidistant quantile mapping. This type of bias correction helps reduce biases in the climate model projections compared to observed weather time series resulting from local climate characteristics such as elevation, topography, proximity to the coastline, and other factors. To accomplish this, quantile mapping matches the cumulative distribution functions (i.e., the quantiles) of observational weather data and climate model data over a coincident time period, and can be applied to dynamically or statistically downscaled climate data. The results from this process were used to estimate a change factor that was applied to NOAA Atlas 14 IDF curves. In the case of the SEMCOG analysis, using dynamically downscaled models captured regional climate processes like lake effects, and quantile mapping helped derive the change factor.

Advantages of this approach include that it is easily automatable and mitigates temporal and spatial scale issues. For example, regional climate models operate at a spatial scale that is too large to examine climate effects at the level of specific infrastructure, such as culverts. However, this method still involves inherent uncertainty associated with extrapolating Atlas 14 data (based on current climatology) to future conditions. SEMCOG recommends that risk-benefit decisions be made across a range of plausible futures given the great uncertainty, and that practitioners choose adaptation measures that can be easily modified and provide ancillary benefits.

4.2.5. Rain Case Study Comparison

The rain case studies highlight how practitioners are implementing a range of different methods to model future rain events. Both PWD and SEMCOG developed future IDF curves for their local regions but took different approaches. SEMCOG used Atlas 14 as a baseline and incorporated outputs from climate models that accurately capture lake effects in the region. To date, PWD has experimented with three different approaches. The first approach involved applying delta change factors to historical hourly precipitation data from a local rain gauge. This approach relied heavily on the assumption that only the intensity, not the frequency or duration, of precipitation events is projected to increase in Philadelphia, as indicated by climate projections. PWD's other two approaches use empirical relationships between temperature and precipitation to develop change factors to apply to Atlas 14 IDF curves. Boulder County's approach incorporates future precipitation in an integrated model that simulates impacts to pinpoint where and what level of interventions might be most effective.

All three case studies demonstrate the importance of accurately capturing local conditions in precipitation projections. For example, PWD found that climate models underestimate precipitation in Philadelphia. Boulder County used historical rainfall data to downscale climate projections. SEMCOG found that a combination of dynamical and statistical downscaling techniques better captures regional climate processes like lake effects.

In many heavily urbanized areas, extreme rainfall generates large volumes of runoff in less than one day, sometimes within the span of an hour or a few hours. Climate models cannot simulate local and regional events on such short timescales, partly because those events are inherently unpredictable and partly because the models generate results on a 24-hour or daily timescale. Extrapolating sub-daily values from daily data means that sub-daily IDF curves will remain highly uncertain due to the lack of sub-daily data.

4.3. Workshop 3: Wildfire and Urban Planning

Wildfire events are growing in frequency and severity due to an accumulation of fuel, diminishing seasonal snowpacks, and more frequent drought conditions as a result of climate change. An increase in the number of structures located in the Wildland Urban Interface (WUI), the geographical area in which the built environment meets or intermixes with flammable vegetation, is also increasing the risk associated with wildfire events. Almost one third of households in the United States are located in the WUI.

Developing solutions to reduce wildfire-related risks can be challenging given the complexity of wildfire and the numerous factors that influence wildfire behavior (e.g., climate variables like wind and temperature, topography, fuel availability). Projections of future wildfire risk are still an emerging area of science, and, given the extensive damage caused by recent wildfires in the U.S., wildfire resilience planning tends to focus on reducing wildfire risk rather than predicting future wildfire events. The three case studies from the wildfire workshop highlight examples of integrating wildfire resilience considerations in urban planning efforts and providing resources to support individual home-level mitigation strategies.

4.3.1. Presentation: Science on Wildfire

Headwaters Economics ("Headwaters") is an independent nonprofit research group that partners directly with communities to improve community development and land management decisions. They work to understand how current wildfire events are changing and promote effective strategies and tools for fire-adapted communities. Six types of strategies have proven effective at reducing wildfire-related risks: hazardous fuels reduction; safe and effective emergency response; ignition-resistant structures; codes, zoning, and ordinances; resilient infrastructure; and strategic public investment. Wildfire mitigation strategies at the individual home level are not sufficient given how rapidly wildfires can spread across a community through embers and home-to-home ignition. Community-level wildfire resilience planning coupled with home mitigation strategies is essential for reducing the risk of urban fire disasters.

Headwaters emphasizes the importance of understanding which locations and people are most at risk before beginning to implement wildfire risk mitigation strategies. There are several tools available to understand current wildfire risk, such as the Wildfire Risk to Communities tool which provides interactive maps and charts of wildfire risk at the community-level across the U.S.[14] The tool uses the Rothermel-based fire behavior models from the United States Forest Service (USFS) and historical weather data to determine the probability of fire occurrence and intensity. A recent (May 2024) update to Wildfire Risk to Communities uses more recent weather data to better reflect recent climate change. The tool accounts for where structures and people are located to identify which communities are most at risk. The tool also includes data on populations that may be disproportionately impacted by wildfire due to socioeconomic factors. Examples of applications include smoke and evacuation planning and identification of vulnerable populations that need cost share programs or greater recovery assistance.

4.3.2. Case Study: Austin, TX

When developing an approach to wildfire resilience, the City of Austin prioritized building a comprehensive picture of wildfire risk that is also inclusive and equitable. Many models of fire behavior are heavily weighted towards fire intensity and consider the areas with heavy vegetation and fuels to be at greatest risk. However, Austin has a diverse fire ecosystem, with grasslands making up most of the eastern portion of the city, where underserved populations are concentrated. This area can experience fast moving grass fires that very quickly reach older homes and communities with fences, which are more prone to ignition. Many older homes were built before Austin implemented its WUI building codes. Underserved communities also tend to have limited capacity to recover following fires, further exacerbating wildfire impacts in the area. To accurately capture fire risk in this region, the City incorporated new components into their fire model, including rate of spread for grass fires. Making this update to their fire model allowed the City to assess potential fire impacts across the region including the eastern portion of the city more sensitive to fire damage.

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[14] Other tools that Headwaters Economics has helped develop include the Unequal Impacts of Wildfire tool and the Rural Capacity Map.

Austin's approach for understanding future climate change in the context of the City's day-to-day operations and assets focused on information needed by decision makers. Climate projections alone were not sufficient for communicating increasing wildfire risk. For City staff to understand how their work and infrastructure could be affected in the future, it was necessary to connect the climate data to decision-making. To do this, the City conducted a vulnerability assessment of each department's critical assets to understand the exposure and sensitivity of each asset to wildfire and related hazards. The assessment focused on the thresholds at which each piece of infrastructure was affected (e.g., at what temperature or degree of fire). The City then used climate projections to determine how the likelihood of certain events may increase and presented both those results and potential related costs to each department. The assessment identified four focus areas to increase resilience: emergency response, staff safety, existing facilities and infrastructure, and new facilities and infrastructure. In addition to increasing resilience through emergency response and infrastructure management, Austin also participated in Headwaters Economics' Community Planning Assistance for Wildfire program in 2016 to identify specific strategies to reduce wildfire risk through land use planning. This program led to a set of recommendations which spanned four categories: improve understanding of WUI risk, address wildland fire in Austin's plans, improve land use tools to reduce wildfire risk, and facilitate a systemic approach to wildfire resilience.

The Austin Travis Community Wildfire Protection Plan (CWPP) is based on a systematic approach to wildfire resilience that begins with support from leadership, includes staff from all city/county departments, and leverages grassroots or community-based efforts to ensure public engagement and support for risk reduction strategies in the community. A working group of collaborators across the City and county formed during plan development to ensure all aspects of wildland planning were represented. The City is currently updating this plan, which will explicitly consider future climate projections and have broader inclusion of diversity and equity considerations. The original CWPP and the forthcoming update will encompass the tenants of the National Cohesive Wildland Fire Strategy. This will maintain continuity between local state and federal initiatives.

4.3.3. Case Study: Ashland, OR

The City of Ashland has different planning documents that take climate science into account. For example, the City's Climate and Energy Action Plan and their Natural Hazard Mitigation Plan facilitate climate resilience efforts. The most relevant plan for wildfire mitigation in the City is the 2016 Ashland Forest Plan, which includes a chapter on climate change. In 2023, the City enhanced the consideration of climate change in this plan by adding a Climate Change Addendum[15] with specific planning and management recommendations to mitigate wildfire-related risks and help forests transition to better suited species as climate change progresses. The importance of the natural environment is emphasized throughout Ashland's community planning efforts. The City completed a study on green and gray infrastructure that identified ways to

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[15] This document is not currently available online.

mitigate wildfire risk through both proactive planning and nature-based solutions.[16] The City has done extensive wildfire fuels reduction on natural areas inside and surrounding the community, reducing the possibility of severe fire directly impacting infrastructure and private property, one of the green infrastructure strategies.

Examples of Ashland's efforts to mitigate wildfire-related risks include the expansion of the wildfire lands overlay in the City. In Oregon, 'overlay' refers to a geographical area where planners can apply specific conditions to future development. In 2018, the City expanded the wildfire lands overlay to include the entire Ashland community, which allowed them to implement land use codes that required defensible space for all new construction. However, retrofitting pre-existing construction to meet these standards remains a challenge, which they are trying to address through a FEMA Pre-Disaster Mitigation Grant. The City also adopted the Wildfire Hazard Mitigation section of the Oregon Structural Specialty Code (R 327), which includes fire resistant building material and construction techniques, such as preventing the attachment of a combustible fence to a structure, which reduces the risk of wildfire.

The City also is working to increase their resilience to wildfire by protecting critical infrastructure and resources, such as the City's and electric supplies. Prior to 2014, the City had only one source of drinking water, its forested watershed, which was providing less water due to increasing drought conditions. Drier conditions impeded the City's ability to put out fires. Consequently, in 2014 Ashland connected their water supply to the regional water supply system to provide an emergency water supply for drinking water and firefighting. The City is in the process of relocating their water treatment plant because it is located in a wildfire and landslide-prone area, and wildfires can increase the risk of landslides by changing soil characteristics and impacting regional hydrology. Relocating the treatment plant will help better protect water resources moving forward.

As part of the State of Oregon's sweeping wildfire legislation in 2021, electric utilities like the City of Ashland were required to file a wildfire mitigation plan with the State. The City's plan identifies a suite of improvements that could help reduce the risk of wildfire igniting from the City's electric infrastructure and ways to harden the system from wildfire impacts.

4.3.4. Case Study: California

The California Department of Forestry and Fire Protection (CAL-FIRE) works to increase wildfire resilience across the state. A key focus area for CAL-FIRE is addressing challenges associated with assessing wildfire-related risks due to the uncertainty in future wildfire patterns. Climate hazards like wind, temperature, and precipitation can all affect the frequency or pattern of fire behavior. As these different factors shift, it is difficult to predict which areas will get wetter or drier in the future and consequently how wildfire likelihood (risk) may change. Despite this uncertainty, current climate conditions are justification enough to invest in wildfire resilience, as many regions in the United States are already experiencing devastating fires.

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[16] Nature-based solutions are defined as: "Actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IPCC 2022).

CAL-FIRE's Fire and Resource Assessment Program (FRAP) is responsible for assessing the amount and extent of California's forests and rangelands and analyzing their conditions, in addition to identifying alternative management and policy guidelines. FRAP also develops Fire Hazard Severity Zone (FHSZ) maps, which use reanalysis[17] to improve maps of potential wildfire hazard occurrence based on factors such as fuel loading, slope, and fire weather. These zones inform fire safe regulations across the State, including ignition-resistant building codes, defensible space, hazard disclosure, and other fire safety regulations. FRAP is currently remapping the FHSZ and will soon release their 2023 Assessment, which will provide data to inform decision makers about changing fire risks and help determine funding priorities to increase resilience to wildfires. Another CAL-FIRE program is the new Community Wildfire Preparedness and Mitigation program. This program takes an inclusive and integrated approach to building community resilience by facilitating collaboration across federal, state, and local entities, as well as tribes, non-profit entities, and other stakeholders. Community needs are prioritized, and all aspects of wildfire preparedness are addressed, from fuel reduction to defensible space to land use planning and building codes, with a strong emphasis on wildfire resistance.

CAL-FIRE also has multiple funding mechanisms for wildfire resilience work in California. These include wildfire prevention grants for fuel reduction and wildfire planning and education; $117 million through California Climate Investments (CCI) became available for 2023-2024. The Land Use Planning Program is another way for CAL-FIRE to fund and facilitate wildfire resilience work. These programs prioritize outreach and working directly with city and county planners to keep them informed about the nature of fire hazards and the programs, policies, and incentives available to them. CAL-FIRE's Subdivision Review Program also supports local governments by helping identify and improve fire safety in areas with numerous dwellings on dead end roads.

4.3.5. Wildfire Case Study Comparison

All three case studies focus on developing hazard mitigation techniques and integrating wildfire resilience considerations into urban planning rather than developing and using future climate projections for planning. Wildfires are already causing significant and extensive damage to communities across the United States. All three case studies take a systemic approach to wildfire resilience by incorporating wildfire considerations into building codes and land use plans and working to facilitate implementation of mitigation techniques through targeted assessments and programs. For example, Austin conducted a vulnerability assessment of all city departments' critical assets to identify focus areas to increase resilience to wildfires. Austin also participated in a program with Headwaters Economics to reduce wildfire risk through land use planning. In the case of Ashland, the city incorporated climate change considerations in multiple foundational plans, such as the Ashland Forest Plan and their Natural Hazard Mitigation Plan. Ashland also conducted studies to identify and prioritize wildfire mitigation techniques, such as through their green and gray infrastructure study. CAL-FIRE produces assessment reports that help determine

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[17] "Reanalysis" refers to the use of a model to interpolate observations to create spatially and temporally continuous information about past weather and climate conditions.

where to focus resilience investments. As a state department that is responsible for providing resources to and supporting local governments, CAL-FIRE also maintains fire hazard severity zone maps and has multiple programs and funding mechanisms to facilitate collaboration across different entities and support local mitigation projects.

5. Cross-cutting Leading Practices and Gaps

This section describes the cross-cutting practices and gaps for incorporating climate projections into infrastructure guidelines identified through the workshops. Additional observations arose during the discussion groups conducted as part of each workshop, which validated practices emerging from the case studies. As such, the leading practices are supported by examples from both the case studies and the topics covered by the discussion groups.

Regional guidance should incorporate well-established climate projections and associated uncertainty.
Selecting which climate projections or scenarios to use can be a significant challenge that often hinders planning and design. Having consistent guidance at the regional level can help practitioners allocate more of their time to developing and implementing solutions rather than choosing what scenario to apply. Consistent guidance can also help standardize scenarios across departments and planning decisions. For example, Southeast Florida’s Unified Sea Level Rise Projection recommends sea level projections that local and regional entities can apply to infrastructure projects based on their cost, criticality, and design life. Regional guidance enables communities and practitioners to focus their efforts on developing adaptation strategies, policies, and infrastructure designs using a consistent set of climate projections articulated in the guidance, leading to improved resilience across the region.

Climate projections (for median and high-end scenarios) supported with strong confidence from the scientific community are appropriate for infrastructure applications.
The challenges associated with selecting climate projection(s) with a strong scientific basis are significant. In general, choosing projections with multiple, converging lines of scientific evidence and expert opinion is more appropriate than selecting projections from an individual study with one or a few datasets authored by a small group of scientists. Additionally, ensuring that guidelines can be easily updated as new data and methodologies emerge will ensure resilience actions are responding to the most relevant information.

Selecting which climate projection(s) to use can be more difficult for certain hazards. For example, for sea level rise, the evidence base is more convergent and established than the evidence base for extreme rainfall and wildfire. For all hazards, another main criterion for selecting climate projections is the applicability of the downscaled climate model or data to the local regions. Models, including the background assumptions used in the models, that are reflective of local or regional conditions tend to be more applicable to specific focus regions. Incorporating observations and using them in combination with projections can also help better capture local conditions. All of this underscores the importance of community-led development of climate science information to ensure that specific climate science information is tailored to the needs of a given locale.

Assessing the magnitude of impacts across different levels of projected climate hazards can help pinpoint feasible design criteria.

While many engineers want clear and specific design criteria, this can be difficult to provide for certain design timeframes given the uncertainty inherent in climate projections. Assessing the range of future climate impacts and associated changes in function of infrastructure systems can help pinpoint where design criteria needs to focus on meeting certain functions or thresholds. Both Boulder and SEMCOG emphasized this approach, and it helped Boulder prioritize its investment in transportation improvements.

Easily available and standardized data, especially for existing infrastructure, can help practitioners understand future risks and associated impacts.

Climate projections are just one component of understanding future climate risks. Practitioners also need sufficient data on current infrastructure to understand how it may be impacted by different climate hazards. For example, there may be limited data available on older water infrastructure, which can make it difficult to understand what level of flooding this infrastructure is capable of withstanding. In the case of wildfire, lack of parcel-level information on existing houses is a large barrier to resilience planning. Although there are many wildfire studies completed at the landscape scale, parcel-level information evolves quickly and there is insufficient data to assess wildfire risk at the community scale. Additionally, available data tends to be difficult to use either due to the format of the data or the computing resources required to visualize or analyze the data. Throughout the workshops, participants emphasized the importance of having up-to-date and standardized data across projects and applications when developing and implementing infrastructure guidelines.

Practitioners need approved methods and design criteria for incorporating climate change in planning and design, including likely and high-end projections in guidelines that clearly explain when each projection should be used in infrastructure design.

Deciding whether to provide a single basis or climate projections or a range of projections can be a significant challenge when developing climate-resilient infrastructure guidelines. It can be useful for practitioners to evaluate multiple estimates during a risk assessment or the sensitivity analysis phase of a project design, but they will ultimately need to identify design loads and associated criteria given the specifics of the infrastructure project.

It can be useful to present two future climate scenarios and offer recommendations of how to choose between the two. Project factors such as criticality, cost, and complexity were identified through the case studies as factors that may help distinguish between when to apply a most likely future climate scenario versus a high-end future climate scenario. For example, all of the sea level rise case studies included in Workshop 1 distinguish between the most likely and high-end estimates, though they include varying levels of detail. For example, NYC's guidelines provide detailed, step-by-step instructions for selecting which sea level rise estimates to use based on the project specifics, whereas South Florida's guidelines recommend which sea level rise projections to use for three broad categories of projects.

Some participants found that being too specific can be just as challenging as being too broad. For example, San Mateo County in California attempted to provide a single number for private developments in the Bay Area but received significant pushback because developers considered the guidance too rigid. A potential solution is to provide specific design criteria with an option for engineers/designers to engage with the climate planning agency if they find it infeasible to follow the guidance recommendations. Philadelphia used this approach and found it helpful for allowing some flexibility in their guidance. Philadelphia also included flexibility in their guidelines by allowing for adaptive management plans, especially for assets built to last to the end of the century or beyond. In this case, engineers can build to a lower design flood elevation than the recommended design criteria provided there is an approved justification and adaptive management plan.

Prioritizing practitioner needs and intended application throughout the development of planning and design guidance can help ensure that guidelines are useful and increase adoption by infrastructure operators and managers.
Practitioners need design guidelines that are practical and provide a good understanding of the context for information use (or ‘use context’). The use context includes consideration of who is responsible for the design and implementation, and what data or information is needed to effectively do their job. Participants emphasized the importance of determining the purpose of the guidelines and aligning priorities across agencies from the beginning of guidance development in order to make it as useful as possible. For example, PWD intentionally collaborated with engineers when developing their guidelines to ensure it would be accepted and adopted by the entire water department. NYC convened a working group made up of representatives from more than 15 city agencies to collaborate and advise on their guidelines. Similarly, Austin worked with multiple departments when conducting their vulnerability assessment.

From developing to implementing infrastructure guidance, inclusive, accessible, and sustained community engagement with a diverse group of stakeholders can help advance equity and ensure guidelines and risk reduction strategies are tailored to community needs.
Many practitioners emphasized that communication between planning agencies and the community is critical. Additionally, making the guidance development process a public and transparent one is essential for building trust and confidence. Extensive community engagement where local elected officials, subject matter experts, and designers and engineers exchange knowledge, information, and views on project criticality, cost, and other infrastructure considerations can improve guidelines. Given that minority groups are generally underrepresented within both the scientific community and politics, it is essential to ensure their voices are represented throughout the decision-making process. Direct engagement with these groups can help decision makers and practitioners better understand community and underrepresented groups' needs and priorities and how the infrastructure will be used.

There are many ways that practitioners are actively working to advance equity and climate justice through resilient infrastructure planning, from developing metrics to evaluating equity when prioritizing projects to engaging directly with communities when designing and implementing projects. For example, Virginia Beach developed a metric to evaluate equity and climate justice as a factor in project prioritization. The goal of the metric is to develop a more objective way of understanding which projects would provide more benefits to different groups.

Boulder County is also incorporating equity considerations in their project prioritization process through the creation of maps that show where transit-dependent populations are concentrated.

Austin, Texas ensured its approach to wildfire risk is inclusive and equitable by updating their fire model to account for fast moving grass fires that impact underserved populations in the eastern portion of the city. Philadelphia, Pennsylvania is currently working on a community-led and created flood resilience plan in Southwest Philadelphia to help avoid top-down solutions. They presented the community with an array of different project options and gave them the opportunity to both share their vision and determine the most feasible combination of the options. Philadelphia is also working with the Water Utility Climate Alliance (WUCA) and has an equity committee that is working to compile different case studies of how other cities and utilities have approached equity and climate justice. Additionally, there are many ongoing efforts to understand how certain populations may be disproportionately impacted by extreme weather events. For example, SEMCOG is currently working on a study with NOAA to understand how different social groups are affected when critical access routes are flooded.

When developing and implementing guidelines, considering multiple climate hazards and local stressors that may create cascading impacts can help ensure a comprehensive risk management approach.

Understanding how multiple events and hazards interact with one another is essential for identifying all potential risks to a project or community. A compound event occurs when multiple climate hazards occur in combination, while cascading impacts describe a chain of related impacts set off by one or more climate events. Compound events often lead to cascading impacts and can cause greater damage and losses than individual events, particularly for already stressed and overburdened communities, governments, or other organizations. Consulting people with expertise regarding interconnected systems and impacts can provide some insight into compound events and potential cascading impacts. For example, compound flood modeling can identify how certain factors could exacerbate flooding due to sea level rise and extreme rainfall. Practitioners are increasingly exploring ways to integrate hydrologic, hydraulic, and hydrodynamic flood models to examine compound flood modeling, especially in urban environments with more impervious surfaces.

Wildfires can lead to cascading impacts by contaminating water supply and affecting other critical systems, among other examples. Wildfire smoke can also have broader health-related impacts on communities, even if they were not directly impacted by the fire. For this reason, taking a systematic, integrated approach to community resilience is especially important for increasing resilience to wildfire into infrastructure and system planning. Comprehensive approaches include both community-level wildfire resilience planning and strategies and individual home-level fireproofing. However, many participants noted how capacity limitations and a lack of incentives can be significant challenges for advancing implementation of wildfire mitigation strategies at the home level.

Effective communication of scientific concepts, easily accessible tools, and training materials on how to use climate-resilient design guidelines promote the adoption of guidelines by infrastructure operators and managers.

Decision-support tools that practitioners can use on a case-by-case basis can be a useful complement to climate guidelines. For example, NYC's guidelines provide design flood elevations relative to a number of important infrastructure considerations, and the guidelines integrate NYC's Flood Hazard Mapper. This easily accessible online tool provides interactive maps of coastal flood projections as well as base flood elevations. Similarly, the Florida Sea Level Scenario Sketch Planning Tool can be used alongside Southeast Florida's sea level rise guidelines to assess the vulnerability of transportation infrastructure to current and future flooding.

Throughout the workshops, participants highlighted the need for improved communication between practitioners and scientists, as well as improved training materials and tools, to bridge the gap between climate science and its application to infrastructure planning. Easily accessible data is especially important for rural and lower-capacity communities that may not have data scientists or climate professionals on staff. Participants also emphasized the need for scientific translators who understand practitioners' concerns and can help make climate science more actionable.

Increased collaboration across disciplines and applications is needed to address climate risks and incorporate resilience in infrastructure planning more effectively.

Challenges associated with silos in infrastructure planning and climate resilience efforts were highlighted throughout the workshops. Designating a local champion and providing top-down incentives can help break down silos and address future climate impacts on infrastructure across multiple agencies and jurisdictions. Although community engagement and bottom-up approaches are essential for incorporating equity and environmental justice, some top-down pressure can also help foster collaboration and coordination. For example, federal grants that require collaboration can be very effective at increasing communication across different agencies. At the local level, identifying champions within departments who attend larger, decision-making meetings can also help promote climate resilience efforts to a broader audience.

For some, developing new task forces, programs, or working groups is helpful for breaking down silos. For example, Philadelphia's Flood Risk Management Task Force is an inter-departmental task force that builds collaboration among City agencies around flood risk management. The Task Force is made up of almost all departments that address flooding and its impacts, from the Department of Emergency Management to PWD to the Office of the Director of Finance. Consistent communication is a key component of the Task Force – they have hybrid meetings quarterly and work to facilitate the sharing of resources, data, and other information across departments. In Austin, Texas, integrating wildfire considerations in land use planning has been essential for increasing community resilience. When developing the Austin Travis Community Wildfire Protection Plan, the City formed a working group of collaborators across the city and county to ensure all aspects of wildland planning were represented in the plan. For others, regional entities or compacts are helping address sea level rise issues across jurisdictional lines and increase collaboration across disparate agencies. Examples of successful regional entities include the San Mateo County Sea Level Rise Agency in California, the South Florida Regional Compact, and the Delaware River Basin Commission.

Establishing shared understanding and a working knowledge base and terminology with decision makers can help facilitate intra- and inter-agency coordination.
Ensuring decision makers have some baseline understanding of climate change projections and impacts is helpful for overcoming challenges related to communication and encouraging investment in climate resilience efforts. Having more local agencies with teams dedicated to climate resilience planning or cross-agency committees can also be helpful for facilitating knowledge sharing as they can all speak the same language across agencies. For example, all of the sea level rise case studies included a committee or working group made up of multiple city agencies and departments, which also reflects coordination across different infrastructure systems, such as housing and transportation.

A significant challenge for practitioners when communicating with decision makers is determining what level of detail to provide. For instance, in some cases, decision makers do not need to know everything about the science to make a decision, but in other cases, a deeper understanding of earth system processes may be required. Detailed understanding and mastery of concepts is often most relevant for smaller departments or groups that either work across agencies or work on specific, large-scale projects or plans aimed specifically at reducing climate hazards.

6. Summary and Next Steps

The workshop series provided a unique opportunity for practitioners from around the United States to convene and share leading practices, lessons learned, and challenges associated with incorporating climate projections into infrastructure guidelines for sea level rise, rainfall, and wildfire. Although challenges and gaps remain, the workshop series helped identify current leading practices for developing and implementing climate-resilient infrastructure guidelines.

Approaches to incorporating climate science information into infrastructure planning and design vary for different climate hazards. Of the three hazards covered in the workshops, sea level rise has the most mature body of science and, to date, this hazard has been incorporated into infrastructure guidelines most frequently. Sea level rise guidelines generally incorporate both likely and high-end estimates for multiple emissions scenarios and timeframes to support engineers in selecting design flood elevations. Selecting which sea level rise estimate to use is primarily based on the project’s location, design life, criticality, and investment level. In the case of rain and urban flooding, practitioners are implementing a range of different methods in order to develop future-adjusted IDF curves. When incorporating precipitation projections into infrastructure guidelines, many practitioners spend most of their time and resources developing projections that accurately reflect local conditions. Finally, practitioners working to advance wildfire resilience are generally not relying on future climate projections. Rather, they are prioritizing mitigation efforts and incorporating wildfire considerations into building codes and land use plans.

The diverse collection of case studies and presentations included in the workshop series highlights the extensive work happening across the U.S. to advance climate resilience through infrastructure design and community planning. The approaches used to address future climate change vary significantly based on the hazard and location, as well as the capacity and technical expertise of the implementing agency or community. Notably, however, many communities across the United States are, in some way, exploring how to incorporate climate science into infrastructure planning or design. This reflects the increasingly widespread understanding that climate change is a pressing problem and implementing science-informed, local resilience measures is vital for effectively mitigating risks associated with climate change in different regions.

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Appendix A. Workshop 1 Discussion Summaries

A.1. Panel Q&A and Key Takeaways

One topic of discussion in the Q&A was how to balance time and resources spent on choosing a sea level rise projection versus modeling flood risk. Jurado noted that in the case of Southeast Florida, updating all the models that are based on the sea level rise projection can take several years and is a much more time-consuming task than updating the projection itself. Behar emphasized that more resources should be spent on flood risk management, but the sea level rise projection forms a strong underpinning for that. Another main topic of discussion was the selection of critical time horizons. The panelists highlighted the challenge of reconciling asset-scale time horizons with community-level planning efforts and timeframes. Practitioners are also limited by the existing built environment and need to consider where it actually makes sense to develop in the future under different sea level rise scenarios. Finally, given that coastal flood risk is complex and driven by multiple hazards, Behar emphasized the need to go beyond sea level rise and consider the way different coastal hazards can interact and increase flood risk.

There were several overarching takeaways from the Panel Presentations. There is a need to make climate science information more accessible and actionable for practitioners. Selecting from the range of available projections remains a challenge, and the choice of a sea level rise projection can significantly influence future adaptation costs. Adopting new projections remains a challenge as new scientific information is released frequently, and it takes time to update guidance documents and related tools. Results from a global survey indicate that there is no global standard for incorporating sea level rise projections in planning, and that localized sea level rise projections and local capacity building are high priority needs.

A.2. Discussion Group Summary

A.2.1. What is your main priority when incorporating climate projections into infrastructure planning?

The main priority for most practitioners is engaging with communities to ensure the guidance and the process used to develop the guidance are transparent and accessible to the public. Past decisions have led to a lot of mistrust, and having a transparent, community-centered process for developing guidance can help earn back trust and make community investment decisions more inclusive and equitable in the future. In order to get community support for long-term investments, it is also important to communicate the benefits of resilient infrastructure design from the beginning and highlight the risk reduction that could result. Having transparent and defensible guidance is also essential to prepare for potential litigation or policy pushback in the future.

Another main priority for practitioners is having confidence in the choice of climate projections. There are multiple components to this, including consensus around projections that are well-established, selection of timescales and scenarios, and understanding the uncertainty in the projections. One challenge is selecting a timeframe that is long enough to serve the project's intended functions, but not so long that it results in unnecessary costs by being too risk averse. It is also difficult to understand relevant timeframes in the context of communities. Given that communities will exist long after individual infrastructure projects, community needs should be centered throughout the development of infrastructure guidelines, especially when selecting timeframes and scenarios and accounting for infrastructure interdependencies. It is also important to effectively communicate the uncertainty with the public and relevant stakeholders/decision makers. Many practitioners also prioritize the consideration of multiple hazards (i.e., erosion, storm surge, other water level drivers) and how they can compound each other, creating cascading impacts on multiple sectors.

Other priorities that were important to some practitioners include ensuring the guidance is interoperable and protecting natural features. Although baseline consistency is important when incorporating projections into infrastructure planning, it is also important to have flexibility so the guidance can be used for multiple types of projects by multiple agencies. To do this, it may be helpful to align priorities across agencies from the beginning of guidance development and determine the types of infrastructure the guidance will be used for. In order to protect natural features and areas, practitioners should ensure that new infrastructure projects do not disrupt existing communities and preserve essential resources. Finally, some practitioners prioritize having a reopener provision of re-visiting and updating the guidance every few years to incorporate new findings.

A.2.2. What criteria are important to consider when choosing climate models or data?

Discussion of climate model/data criteria was covered to some degree under all four discussion questions. Most practitioners agreed on three main criteria for selecting climate models or data for their guidelines. The first is the inclusion of relevant temporal and spatial scales. Many practitioners need regionally available, downscaled climate data, and spatial resolution can be a challenge when selecting from available climate data to use.

The second criterion is the applicability of the downscaled climate model or data to the local region. Models, including the background assumptions used in the models, should be reflective of local conditions in order to be applicable to the focus region. Additionally, observations should be incorporated and used alongside projections. This can also be helpful for determining if model conditions are reflective of real events.

The final criterion is consensus and consistency in the projections. The projections should come from established scientific literature or research, and peer review should not be the only requirement for determining if science is established. This also includes having coherent guidance at national and local levels. The maturity of projections and how widely they have been used by other agencies or entities is another way to determine whether there is consensus around using particular projections. Consensus and consistency is especially important when selecting high-end estimates of sea level rise. As mentioned in Behar’s presentation, high-end estimates should have multiple lines of evidence and be reasonable as opposed to representing the worst case scenario (i.e., use the median of the RCP 8.5 scenario rather than an extreme/H++ scenario).[18] The scientific community should also have strong confidence in the projections.

A.2.3. What are the key ingredients to successfully incorporating climate projections into infrastructure planning?

For most practitioners, there are three key ingredients required to successfully incorporate climate projections into infrastructure planning. The first is a clear understanding of what the asset is, how adaptable it is, and what potential future options for the asset are (i.e., can it be elevated or relocated in the future).

It is important to understand all potential threats to a project in process and determine whether or not the asset needs to be built at that site based on its criticality. For example, some assets or infrastructure, like a major train terminal or an electrical substation, are far more expensive and difficult to move, whereas other assets/infrastructure, like a parking lot or recreational fields, are less expensive and easier to move. A component of this is prioritizing certain infrastructure, which could be completed through a vulnerability assessment. Multiple future scenarios should also be considered.

The second key ingredient for most practitioners is inclusive engagement with communities and local experts and thoughtful consideration of their needs. Many practitioners emphasized that communication between planning agencies and the communities they are planning for is critical. Additionally, making the guidance development process a public and transparent one is essential for building confidence. An important component of this is incorporating extensive community engagement and vetting. A breadth of interest groups should be represented in order to bring together local elected officials to become champions, encourage deep uptake by communities, and create good lines of communication. This also includes collaborating with local experts who are on the ground and understand how different types of infrastructure are already being affected by sea level rise and other hazards. Additionally, when engaging with the public, providing examples of how standards could have been applied to recent development projects can alleviate concerns.

The third key ingredient for most practitioners is consideration of multiple hazards and cascading impacts. Sea level rise does not occur in a vacuum, and understanding how multiple coastal hazards can compound one another and create cascading impacts is essential for understanding all potential risks to a project or community. This includes performing compound flood modeling. Even if only one hazard is included in the guidance, people with expertise regarding a variety of connecting systems and impacts should be consulted.

Other key ingredients that some practitioners mentioned include case studies of successful projects, preservation of existing community spaces and resources, flexibility in the implementation of guidance, and strong leadership. For both practitioners and the public,

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[18] van de Wal, R. S. W., Nicholls, R. J., Behar, D., McInnes, K., Stammer, D., Lowe, J. A., et al. (2022). A high-end estimate of sea level rise for practitioners. Earth's Future, 10, e2022EF002751. https://doi.org/10.1029/2022EF002751.

examples of resilient projects and solutions can help manage expectations and alleviate concerns for community members in addition to demonstrating to practitioners what implementation of the guidance could look like. Some practitioners also highlighted that there should be a balance between resilient infrastructure projects and existing community spaces and resources. For example, shorelines are meant to be accessible and people should be able to enjoy the waterfront. Guidelines should also incorporate flexibility to allow for adaptive management of infrastructure projects. For example, although the current design elevation should be the focus now, project designs should account for potential increases in the design elevation in the future. Finally, some practitioners emphasized the importance of having strong leadership that is actively engaged in climate resilience work and is dedicated to the long process of developing climate resilient guidelines. It is especially critical to engage elected leadership and break down silos to facilitate better planning.

A.2.4. What are the primary barriers to incorporating climate projections into infrastructure planning?

There are three main barriers that many practitioners face when incorporating climate projections into infrastructure planning. The first is being unsure of which projection to include, as practitioners are not necessarily qualified to choose climate models. There is a need for scientific translators who understand practitioners' concerns and needs and can help bridge the gap between scientific understanding and its application to infrastructure planning. Translators in government are also needed to help make government reports more easily digestible or usable by the public. However, it is also important for practitioners not to let uncertainty or challenges in selecting projections stagnate decision-making. Practitioners can develop guidance with the resources or data available to them now and still update or revise that guidance as needed when new or better information becomes available.

The second barrier for many practitioners is reconciling different projections. This includes navigating different sets of guidance at local, regional, and national levels. For example, some local governments may choose to use IPCC projections, but this can become complicated when the federal government encourages the use of different projections. Additionally, some practitioners consider state- or regional-level guidance to be too conservative for the locality they are in. For practitioners from states with more conservative governments that do not provide much state or local guidance, regional- and national-level guidance is essential for decision-making. Another challenge is reconciling changes in projections and the release of new science. Having a regular cadence of updating guidelines can be helpful for this.

The third barrier for many practitioners is coordinating and communicating with multiple stakeholders. Advancing equity requires buy-in from stakeholders at every level of the process, from planning through the operations and maintenance stages. However, it can be difficult to make community members feel comfortable taking part in the discussion, especially when they are not familiar with climate science. In the case of the Bay Area, workshops and technical assistance were offered to community based organizations to explain sea level rise and other relevant issues, and pre-meetings before community meetings were held to explain what information may be covered. Additionally, participating in stakeholder engagement often requires significant time commitments. A potential solution to this could be providing childcare for public meetings or paying community based organizations to attend. It can also be difficult to explain and translate the gravity of thought processes to local communities in a way they can understand and that resonates with them. Practitioners also struggle with frequent reeducation with communities, even with guidance updates, because they are working with a dynamic population.

Other barriers some practitioners face include measuring success, high cost and time commitments, insufficient local capacity, reconciling new guidance with existing codes and standards, and lack of monitoring data. Stakeholders often want evidence that the asset or community will be protected by the resilience measure/project. However, most projects will only mitigate a certain level of risk, not all risk. This can be difficult to convey outside of technical groups that understand that finite risks associated with climate change will never be completely removed, but lessened through different measures. It is also difficult to quantify co-benefits related to nature based solutions and other resilience measures, especially when the benefits are largely environmental. This can be especially challenging when applying for funding. For some practitioners, time and cost issues are the biggest challenge, especially when working with data at a finer resolution. Additionally, if data is not available, creating it can be costly. Other practitioners struggle with capacity challenges. For example, smaller local governments are less likely to have sufficient capacity to develop guidance and update their codes and standards. This is especially true for under-resourced communities. Finally, a challenge for some practitioners is lack of sufficient monitoring data. For example, some practitioners emphasized the need for more tide gauges and guidance on incorporating datum updates into sea level rise projections.

Appendix B. Workshop 2 Discussion Summaries

B.1. Panel Q&A and Key Takeaways

One topic of discussion in the Q&A was about determining the best approach to model future rainfall/precipitation and flood events and the tradeoffs of different approaches. All panelists agreed that it is important to consider multiple approaches at the outset to understand their strengths and limitations. PWD balanced the needs of different units of their organization with guidance standardization to ensure some amount of climate risk could be incorporated into projects. Boulder County prioritized the ability to look at tradeoffs of different interventions and adaptations. DeGaetano and Butcher agreed that utilizing different approaches is helpful to build a realistic examination of flood risk given the novelty of both the science and its applications.

Regarding uncertainty in climate science, panelists agreed that it is important to recognize and communicate uncertainty in precipitation projections. They also recommended that, given the inherent nature of uncertainty in climate projections, the focus should be more on determining the relative change in flood risk. Butcher noted that although using climate projections to inform infrastructure design is an evolving practice, the goal is to determine whether conditions will likely get much worse. Boulder County addressed this by assuming a higher emissions scenario to examine the worst case for potential impacts. DeGaetano emphasized that the ultimate decision to use a particular value ought to result from discussion between climate scientists and practitioners. In the case of PWD, the CCAP first recommends a narrow range of values to engineers, and then discusses risk tolerance and the criticality of the asset to determine which of the values within the range to use.

The discussion also considered other factors, such as cost and feasibility, that influence how climate projections are used in design guidance. Boulder County is constrained with a relatively limited budget and the need to focus on maintaining existing infrastructure, so it applies official guidance on a case-by-case basis that considers the cost of a given project. A consultant to PWD suggested prioritizing projects for adaptive design by determining a threshold for significant damage and whether that threshold is within the range of likely impacts. DeGaetano emphasized that it is important to consider the assumptions that feed into climate projection analysis (e.g., how much the climate will change), since they drive most of the uncertainty.

There were several overarching takeaways from the Panel Presentations. One is that NOAA Atlas 14 is the standard data/analysis in use, so several of the methods use change factors for Atlas 14. Secondly, there are challenges with calculating sub-daily rainfall/precipitation values (e.g., 15 min or 1 h events). Sub-daily and even sub-hourly rainfall are really important for heavily urbanized areas because impervious surfaces increase runoff. However, neither regional nor GCMs can simulate convective thunderstorms and other small weather patterns that vary on such fine temporal and spatial time scales. Lastly, although there is a certain level of uncertainty that is inherent in creating precipitation projections, the goal should be to assess the relative change in flood risk to help prioritize the infrastructure to focus on and the adaptation investments.

B.2. Discussion Group Summary

B.2.1. What are the biggest challenges with developing the guidance and implementing it?

The main challenge for most participants with developing and implementing climate change guidance is communicating the uncertainty in climate science to relevant stakeholders, such as elected officials, the public, and practitioners. One component of this task is communicating the non-stationarity of future climate conditions so stakeholders understand why future guidance updates are inevitable. Additionally, many engineers want clear and specific design criteria, which can be difficult to provide for the 25 to 10c0 year design timeframes given the uncertainty in climate projections. However, some participants warned against exaggerating uncertainty so much that it leads to inaction. For instance, although the rate of change in future rainfall is relatively uncertain, there is general consistency across the models that precipitation will increase.

Participants emphasized that there is a lot that can be done to increase climate resilience despite the level of uncertainty in climate projections. Participants have also struggled with communicating the strengths and weaknesses of climate models for different applications. For example, sub-daily/sub-hourly rainfall data is needed for design by many practitioners, but downscaling climate models to that time scale increases uncertainty. Heavy rainfall on sub-daily and sub-hourly scales is often very localized. For example, the location and timing of convective thunderstorms can be difficult to predict in real-time, much less 10 to 30 years in the future, and their duration and intensity can vary from one town or neighborhood to the next. Experts in climate science and climate communication are needed to help practitioners and decision makers understand these processes and appropriately apply science. Some participants suggested that having training materials ("Climate Modeling 101" for example) could be helpful for understanding climate projections and how to apply them.

Another challenge for many participants is coordinating across multiple entities, such as multiple jurisdictions and levels of government to infrastructure owners. For example, stormwater management and climate resilience projects are siloed, with their own standards and priorities, making it difficult to achieve consensus. Another barrier to coordination between jurisdictions is lack of time and capacity, as many local governments in particular are overworked and under-resourced. Lack of coordination also limits the transfer of knowledge across departments or agencies, which can impede implementation efforts if the agencies responsible for implementing guidelines do not have the technical understanding to use them. It can also be difficult to get consensus on acceptable risk levels because risk is very context- and community-dependent. Additionally, different sectors face different risks and have different processes and asset types, further complicating efforts to develop consistent standards and approaches.

Practitioners need design guidelines that are practical and provide a good understanding of the context for information use (or 'use context'). The use context includes consideration of who is responsible for the design and implementation, and what data or information is needed to effectively do their job. Participants emphasized the importance of determining the purpose of the guidelines to make the guidance as useful as possible. Another key component is finding a balance between specificity and flexibility. Many engineers need specific guidance (i.e., a single number for design criteria, such as maximum rainfall intensity), however, some participants have found that being too specific is just as challenging as being too broad. For example, San Mateo County in California attempted to provide a single number for private developments in the Bay Area but received significant pushback from developers because their guidance was considered to be too rigid. A potential solution is to provide a specific design criteria with an option for engineers/designers to engage with the climate planning agency if they do not want to follow the guidance recommendations. Philadelphia used this approach and found it helpful for allowing some flexibility in their guidance. Another solution that Philadelphia has used to include flexibility is allowing for adaptive management plans, especially for assets built to last to the end of the century or beyond. In this case, engineers can build to a lower design flood elevation than the recommended design criteria provided there is an approved justification and adaptive management plan.

Participants face challenges related to engagement, including getting buy-in from key practitioners and stakeholders throughout planning and implementation. Engaging communities can be especially challenging in low-income, disadvantaged, and historically disinvested communities that tend to interact less with the government. In more conservative regions, participants struggle navigating outreach when some community members do not trust climate science. It can also be difficult for participants to maintain dialogue with communities, as community members tend to engage immediately following severe events. Additionally, although many participants want to prioritize equity and climate justice, it can be challenging for them to determine where disadvantaged communities actually are located within a larger community. Participants have found that census and socioeconomic data do not always accurately capture where disadvantaged communities are located, affecting downstream decision-making and project prioritization.

Funding for both the development and implementation of guidelines is also a challenge for many participants. Although federal funding for climate resilience efforts has increased, there is simply not enough funding available relative to the amount of work needed. It can also be difficult to develop benefit cost analyses, which are often required for federal funding applications, given that certain resilience benefits are hard to quantify. Lack of funding can also be a barrier to accessing vital climate and technical expertise, as both hiring experts and building in-house capacity can be costly. Despite funding challenges, many participants have found creative solutions to facilitate the implementation of different resilience initiatives and projects.

Other challenges include:

- deciphering which climate projections or scenarios to use given the lack of consensus within the scientific community;
- ensuring all required data is obtained and it is up-to-date and standardized across projects and applications in a community or region;
- staying up to date with the continued development of climate science and updating guidance, as new research/updates will continue;
- not having sufficient data to understand future risks for current infrastructure; and
- increasing compliance given that guidance is often not mandated.

Case Study: Innovative Solutions to Funding Challenges

The state of Michigan does not have a funding mechanism for stormwater infrastructure improvements. One solution SEMCOG found is leveraging planned road improvement projects. For example, when there is a planned road reconstruction project, SEMCOG assesses the condition of the stormwater system or other underground infrastructure at the site. If the underground infrastructure needs to be replaced, SEMCOG can typically secure additional funding to upgrade the stormwater infrastructure at the same time because the cost difference is relatively minimal if the roadway area will already be under construction. However, one caveat to this approach is that upsizing pipes in one location may lead to new issues downstream of the site.

B.2.2. How can stormwater and floodplain design better address equity[19] and climate justice?

Participants felt that the main way equity and climate justice can be addressed in stormwater and floodplain infrastructure design is through intentional and thoughtful community engagement with diverse groups. Given that minority groups are generally underrepresented within both the scientific community and politics, it is essential to ensure their voices are represented throughout the decision-making process. Direct engagement with communities can help decision makers and practitioners better understand community and underrepresented groups' needs and priorities and how the infrastructure will be used. Community engagement can also help avoid investment in solutions that would not benefit the community. It is important to understand the history or root cause of existing inequities and to identify current responsibilities for addressing inequities in future projects. Given that climate change often exacerbates existing inequities within communities, it is essential to engage with community partners who can share their knowledge and experiences to help address blind spots that have previously existed in infrastructure design. Although data and metrics are important and can help identify vulnerable areas, they often do not capture the qualitative input and contextual information that only communities can provide.

The importance of having a systematic way of measuring equity and climate justice benefits was highlighted, either through a set of quantitative metrics or some other decision support system. If available, metrics provide engineers with information to help prioritize projects based on equity and climate justice components. Participants emphasized that the development of such metrics should be a transparent and inclusive process that takes into account stakeholder input. A challenge with these types of metrics is that equity and justice issues are often place-based and so, there are no standard metrics—and corresponding strategies—to use. It can also be challenging to ensure that communities have flexibility to customize these metrics based on what is most important to them, while still ensuring the metrics are valid.

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[19] ‘Equity’ was not explicitly defined for participants in the workshops, and participants may have different understandings of what ‘equity’ means. Historically, infrastructure has not been planned or implemented equitably, which is a systemic issue that requires a broader effort than these workshops to address. However, the workshops provided an opportunity to frame important questions and surface important equity-related issues.

Another way to address equity and climate justice is through a comprehensive or systems-based approach to developing solutions. A solution for one issue can oftentimes create unwanted impacts in other areas, so it is essential to look comprehensively at the situation and consider all potential risks. This includes going beyond the project site and considering upstream and downstream impacts, as well as other factors such as land use policies and future development.

It is also important to provide training and resources to educate practitioners and community partners on infrastructure impacts on equity and climate justice. Training for decision makers and practitioners would help them recognize issues of equity within the community so they can incorporate those factors in their existing processes for ranking and prioritizing projects. It is also important to educate practitioners and community partners on why certain areas or populations are vulnerable in the first place. For example, Tribal populations tend to be disproportionately impacted by climate hazards, but some practitioners and community partners have not been educated on the history of forced relocation of Tribes and do not understand the root cause of existing equity and environmental justice issues. Training and educating practitioners and community partners on how to work with Tribes and rebuild trust is essential for developing solutions that are ethical and provide long-term benefits.

Equity and climate justice were priorities for the three case studies presented at the Workshop. Although the guidelines from Philadelphia, Southeast Michigan, and Boulder County do not explicitly incorporate equity and climate justice, each region has ongoing plans or projects to increase consideration of these topics. For example, Philadelphia is working with the Water Utility Climate Alliance (WUCA) and has an equity committee that is working to compile different case studies of how other cities and utilities have approached equity and climate justice. SEMCOG is currently working on a study with NOAA to understand how different social groups are disproportionately impacted when critical access routes are flooded. Boulder County has created maps that show where transit-dependent populations are concentrated to help inform project prioritization.

Additional ways to address equity and climate justice include:

- breaking down silos within governance structures so community partners and practitioners work more closely together;
- sharing case studies and leading practices for incorporating equity in other communities;
- increasing access to green spaces in disadvantaged communities;
- considering how disabled populations may be disproportionately affected by climate hazards; and
- incorporating equity and climate justice considerations in the siting process for projects.

Case Study: Incorporating Equity and Climate Justice

Virginia Beach developed a metric to evaluate equity and climate justice when prioritizing projects. The goal of the metric was to develop a more objective way of understanding which projects would provide more benefits to different communities. For example, if a project was located in a lower income neighborhood, it received more points than a project in a higher income neighborhood. The metric also incorporates factors such as historical and future flood risk at the project site. This metric has proven more successful than a standard benefit cost analysis for understanding where to prioritize investment.

B.2.3. What are some best practices in addressing stormwater management and flooding across multiple agencies and jurisdictions in the face of future rainfall projections?

One best practice is having entities that can facilitate coordination across agencies and jurisdictions to address stormwater management and flooding. Such entities include regional planning or coordination entities like the Tampa Bay Regional Planning Council, as well as task forces made up of multiple agencies or departments, like the Philadelphia Flood Risk Management Task Force. Entities that are specifically created to help foster collaboration and ensure everyone has access to the same information and/or training is essential for building capacity and shifting the narrative that only one agency or entity is responsible for stormwater management and flooding. Another way to foster collaboration is by leveraging existing entities that already have a cross-cutting role, such as Councils of Governments (CoGs) or Metropolitan Planning Organizations (MPOs). Some participants also consider local universities to be helpful partners for collaboration given that they often have more resources and modeling capabilities.

In addition to agencies that can help foster collaboration, more consistent communication and education across agencies and jurisdictions is needed. It is essential that communities and different levels of government are able to communicate clearly with each other, and MPOs are one potential option for bridging that gap and facilitating those discussions. It is also important to educate decision makers on basic climate information and terminology so they can better understand community challenges and potentially incorporate climate resilience in their policies and help facilitate implementation. Having more local agencies with teams dedicated to climate resilience planning is also helpful for facilitating knowledge sharing as they can all speak the same language across agencies.

Having a champion and top-down incentives can also help address future climate impacts on infrastructure across multiple agencies and jurisdictions. Although community engagement and bottom-up approaches are essential for incorporating equity and environmental justice, some top-down pressure can help foster collaboration and coordination. For example, federal grants that require collaboration have proven very effective at increasing communication across different agencies. At the local level, identifying champions within departments who attend larger, decision-making meetings can also help promote climate resilience efforts to a broader audience.

Case Study: Breaking Down Silos

Philadelphia's Flood Risk Management Task Force is an inter-departmental task force that builds collaboration among City agencies around flood risk management. The Task Force is made up of almost all departments that address flooding and its impacts, from the Department of Emergency Management to PWD to the Office of the Director of Finance. Consistent communication is a key component of the Task Force – they have hybrid meetings quarterly and work to facilitate the sharing of resources, data, and other information across departments. The Task Force is actively working on strategic actions to increase flood resilience.

B.2.4. What are best practices for updating guidance as the climate science and/or design considerations change?

A best practice for updating guidance is continuous communication, especially with the public, during guidance development and updates. Given how long it takes to produce guidelines, it is essential to maintain communication with communities throughout the process to ensure that the guidelines are aligned with their needs. Having structured rollouts of updates and notices explaining why the guidelines are being updated and how they are changing can also be helpful for alleviating concerns. In general, it is important to have resources dedicated to explaining the guidance and making it accessible so updates are less shocking or confusing to both the public and users of the guidance.

Another best practice for updating guidance is having a structured timeline for updates so planners and engineers know when to expect new information. One option is to update guidelines every five years or so, which is aligned with the frequency of GCM updates. Alternatively, more frequent updates are helpful so the changes between projections are relatively minimal. However, frequent updates can be frustrating for designers and engineers and can make planning agencies lose credibility. Additionally, waiting too long to update guidelines can lead to a more significant change in the projections, which may be more shocking or confusing for users. Another option is to provide a range of values rather than a single set of design criteria, but that requires more nuanced guidance (as discussed under Question 1).

Another approach is to use dynamic adaptation pathways, including updates to guidelines when a certain threshold is met. For example, the guidelines would not be changed unless a certain percentage increase in the projections occurs or until a characteristic storm reaches a certain threshold. However, there is some disagreement with this approach because it means that adaptation measures, like expensive hardening or elevating infrastructure, are only implemented once the need is identified, at which point it will likely take years to design and build whatever solution is required. It can also be difficult to determine what a reasonable threshold should be for updating guidelines. Some communities and practitioners are more comfortable building for the worst-case future event, even if it is more expensive in the near-term; this approach is still being debated as to when it is a suitable approach from a societal and economic perspective.

For many participants, building flexibility into guidance can make it easier to implement updated guidelines in the future. Having planners and engineers create adaptive management plans, for example, builds flexibility in designs and allows for future changes to projects, which is inevitable as new climate data and projections are released. Taking an adaptive management approach also helps account for how long construction can take.

A best practice for calibrating models is ground-truthing projections with local data and engaging citizen science/engaging the public. For example, Maryland has an app that community members can use to submit flooding photos. Those photos are then connected to high-tide flooding, riverine, and weather data. This approach can help communities and practitioners better understand what impacts look like on the ground and determine how accurately projections reflect local conditions. North Carolina's Department of Transportation flies drones after major hurricanes to record flood levels. This information is then integrated into their modeling process to better calibrate their flood models.

Other best practices include the incorporation of green infrastructure and nature-based approaches in future guidance updates and assessing the success of implementing previous guidelines. Also, understanding how projection updates will affect related planning efforts is essential (i.e., what other plans or tools would need to be revisited if the guidelines are updated).

B.2.5. Emergent Themes

Throughout the discussion groups, other topics emerged that fall outside the specific scope of the discussion questions. These are summarized below.

Multiple participants noted the difficulty of creating easily accessible tools for application purposes. For example, Philadelphia is working to update their flood resilience tool, and although consultants can help develop the tool, the City has struggled to build in-house capacity to use and manipulate the tool for different applications. It would be helpful for participants to have more guidance or a set of standards or principles on what constitutes a good tool. These could include consideration of how best to communicate uncertainties and what climate models can and cannot provide. Some participants also shared new tools they have found interesting, such as Google's new AI flood forecasting model that uses millions of pictures of past flood events to predict future flooding.

Some participants also discussed appropriate levels of climate literacy for civil engineers. Engineers working in the public sector are trying to incorporate climate science into standards, but it is a slow process. There is a risk that if standards are not available for climate projections, then there will be increased future costs following flood events. Some participants identified concerns around litigation. Although engineers are trying to design for future climate impacts, they do not have guidance and may have concerns about getting sued for their designs in the future. Once guidance or standards are available, jurisdictions must adopt them to ensure their implementation.

Appendix C. Workshop 3 Discussion Summaries

C.1. Panel Q&A and Key Takeaways

One topic of discussion addressed successful approaches for understanding future wildfire-related risks. Panelists emphasized the following points:

- The importance of both using recent experiences to guide planning efforts while also ensuring that planning is proactive rather than reactive.
- The value of engaging directly with community members in order to build trust and create an open dialogue around wildfire-related risks and potential solutions.
- Availability of information and resources that would help determine which actions to take to increase wildfire resilience, emphasizing improved predictive models and parcel-level data to inform decision-making.
- More research or data on home-to-home ignition and urban conflagrations would be especially informative.[20]

Another topic of discussion was the importance of integrating wildfire considerations into community planning documents. Panelists noted the following challenges:

- Incorporating wildfire in foundational plans (i.e., community resilience and land use plans) can help facilitate the adoption of new ordinances or codes in the future.
- Carrying out managed retreat equitably given that vulnerable populations tend to be disproportionately impacted by climate hazards but often have limited capacity to relocate.
- Improved communication and modeling techniques are needed to better understand wildfire-related risks and explain those risks and the advantages or tradeoffs of potential solutions to the public.
- Ways to reconcile traditional green initiatives that incentivize higher-density development with the need for defensible space for wildfire mitigation.
- WUI codes that address the hardening of higher-density developments.

The discussion also considered funding for wildfire resilience work. Panelists noted that the majority of their planning efforts are completed by permanent staff using local funding, whereas mitigation or adaptation work in communities is largely funded by grants. For example, Ashland does not have a local funding stream for wildfire mitigation in the built environment and instead relies on FEMA grants to help communities complete defensible space and home-hardening projects. Where possible, Ashland also leverages active construction permits during remodels to include retrofitting to wildfire standards. Panelists also shared innovative ways to increase funding, such as through bond measures or special fees or taxes. For example, South Lake Tahoe has a property tax fee specifically for forest health and fuels treatments. There are also new federal grant programs available, such as the Community Wildfire Defense Program under the Infrastructure Investment and Jobs Act.

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[20] Urban conflagrations are large and destructive fires that spread uncontrollably from structure to structure (IBHS 2023).

There were several overarching takeaways from the Panel Presentations. Understanding wildfire-related risks and developing solutions is especially challenging due to the complex nature of wildfire and uncertainty in future projections (e.g., increasing exposure due to rising temperatures, changing fuel loads, and growing WUI areas). A systematic, integrated approach that includes both community-level planning and capacity-building and home-level fireproofing is essential to effectively increase wildfire resilience. Additionally, community needs should be prioritized when assessing existing risks and developing potential solutions, including direct engagement with a diverse set of community groups to build trust and ensure risk reduction strategies are implemented equitably. More detailed data and models, especially at the parcel level, are needed to help practitioners better understand how wildfire-related risks and vulnerability are changing. Data is most helpful if it is easily accessible and can inform decision-making.

C.2. Discussion Group Summary

C.2.1. What are the main barriers to understanding current and future wildfire-related risks to the built environment and public safety in your region?

A main barrier for many participants is understanding vulnerability across communities. There are many different definitions of ‘vulnerability,’ which can make it difficult for participants to determine which groups, infrastructure, or areas are most vulnerable and should be prioritized. Data availability and quality is a barrier to understanding or quantifying vulnerability, especially at sub-county scales. Another challenge is assessing the vulnerability of existing infrastructure that was built prior to WUI codes compared to new construction.

Parcel-level information on existing houses is a main barrier to better vulnerability assessments. In many cases, property inspections are needed to get accurate data. Although there are many studies completed at scales larger than individual parcels of land or households, parcel-level information evolves quickly and there is insufficient data for WUI purposes. Additionally, the data that is available tends to be difficult to access either due to the format of the data or the computing resources required to visualize or analyze the data.

Discussion of barriers carried over to the second question.

C.2.2. What are the biggest challenges with developing wildfire resilience strategies or plans and implementing them?

The biggest challenges for most participants fell into three main categories: public engagement, funding and capacity for community-level planning, and feasibility of homeowner-level mitigation. These are described in more detail below.

Public Engagement

The biggest challenges for many participants are related to engaging with the public and decision makers. These challenges include effectively communicating how wildfires are changing and risk is increasing, overcoming public perceptions of wildfire-related risks and mitigation techniques, and identifying community partners.

Effectively Communicating How Wildfires Are Changing and Risk is Increasing

More guidance is needed to determine how best to communicate increasing wildfire-related risks to the public and decision makers for the range of interests and desired outcomes. This includes convincing the public of their role in wildfire mitigation. For example, what are effective ways to educate people on home-to-home ignition and how homes can function as fuel for urban conflagrations that will lead to mitigation actions. Additionally, some consider wildfires to be a problem that the government should solve, whereas local governments may see it as the role of the homeowner to mitigate their risk on individual properties. In some cases, there is a perception that mitigating wildfire-related risk is an impossible task, which can result in a lack of action.

Public Perceptions of Wildfire-Related Risks and Mitigation Techniques

The public may not consider wildfire to be a concern because fire departments have historically been very successful at keeping fires out of communities and putting fires out quickly. However, as fuels continue to accumulate and more people reside in the WUI, exposure to wildfire will continue to increase and become harder to prevent and extinguish. Additionally, wildfire smoke is another impact from WUI fire on the community and surrounding areas, even when a fire does not enter the community or a given area.

Communicating this to the public can be challenging, especially in locations that have not experienced recent wildfires or historically been affected by wildfire. Many participants noted how people often struggle to fully comprehend low-probability, high-consequence events, and improved, innovative communication techniques are needed to overcome this barrier. For example, Humboldt County District in northern coastal California has a temperate rainforest climate and has historically been very wet. Research indicates that the region’s trees and wetlands are becoming drier and wildfire likelihood is increasing due to climate change, but county staff have struggled to convince the public of this trend given that the region has not experienced severe wildfires in over 50 years. Even in areas that have experienced recent wildfires, participants noted how the public tends to forget those events relatively quickly and often both underestimate their own risk and overestimate how much work it will take to reduce their risk. When communicating with homeowners, participants suggested it may be helpful to talk about the likelihood of fire exposure on a similar timescale to their mortgage (i.e., 30-year period) rather than discussing annual likelihood.

Some participants also struggle to overcome public perceptions of certain wildfire mitigation techniques for the reduction of risk and/or impacts. For example, some members of the public consider prescribed burning to be dangerous and have protested planned burning. One solution for this is effective messaging and demonstrations to educate the public on how prescribed burning can be done safely. Other participants struggle to get WUI codes passed due to public resistance. Whereas certain codes or wildfire mitigation techniques are obvious solutions to researchers and practitioners, the public may not always understand how those codes and techniques are in their best interest and will help protect lives and properties. Participants emphasized the need to better understand human nature and behavior to improve communication techniques and ultimately increase acceptance of effective solutions.

Identifying Community Partners

Some participants cited the need to find reliable community partners. For example, in California, many people living in vulnerable communities work multiple jobs, so finding people who have the availability to engage can be a challenge. Reimbursing community members for their time is a promising solution, but funds are not always available to do so. Other participants struggle to find communities that are willing to engage due to a lack of trust in the government.

Another challenge is ensuring that community members are involved in the decision-making process. Participants emphasized the importance of treating community-based organizations as equal partners and providing opportunities for them to help develop solutions to increase resilience. In this case, local governments work as facilitators and collaborate directly with community partners. Local governments may benefit from additional support or training to build facilitation skills.

Funding and Capacity for Community-level Planning

At the community level, insufficient funding and capacity are the biggest challenges to planning and implementing wildfire resilience strategies.

Participants noted how local agencies often have to wait for funding that is specific to wildfire resilience and climate change, or need to leverage general funds instead, like emergency response. Capacity can also be a limitation, especially for long-term maintenance of fuels and vegetation, which may require establishing new units to conduct annual surveys and monitoring.

Funding and capacity limitations can be especially challenging for smaller communities that often do not have government employees or community leaders to take on these planning efforts. Smaller communities also tend to be at a disadvantage compared to larger communities that have more staff, professional fire departments, and either experts with the training and knowledge to carry out resilience planning and strategies or the funding to hire consulting firms for assistance. Participants noted that this is especially true for Tribal communities. Additionally, smaller communities often do not have the resources or ability to be competitive in different grant funding cycles.

Feasibility of Homeowner Mitigation

The need for individual homeowner action in addition to community wildfire resilience planning and strategies was highlighted throughout the workshop. However, many participants noted how capacity limitations and a lack of incentives can be significant challenges for advancing implementation of wildfire mitigation strategies at the homeowner level.

The importance of providing homeowners with mitigation techniques that are both feasible and effective was emphasized. For example, asking a homeowner to retrofit their entire home is a significant request for most people given the time commitment and costs required. In addition to financing the retrofit, homeowners may need to find contractors, research suggested strategies or products to implement, and try to find an insurance company that provides discounts or credits for the retrofit. One way to reduce the burden on homeowners is to identify low-cost, easy-to-implement, and highly effective mitigation strategies that homeowners can implement if entire home retrofits are not feasible. Using available data on the effectiveness of different mitigation techniques and cost-benefit analyses, practitioners can present homeowners with feasible strategies that they can implement relatively quickly. For instance, adding a bed of gravel at the base of a home and moving mulch and planting beds can reduce ignition risk is much more accessible than a retrofit that will cost thousands of dollars. Although such strategies do not provide the same level of protection as an entire home retrofit, they can significantly reduce the vulnerability of the property to wildfire-related impacts.

Another major challenge is lack of incentives, especially with regards to insurance for both renters and homeowners. For instance, homeowners may expect to see a decrease in their insurance premium after implementing resilience activities on their parcels, but participants noted that this is often not the case.

Wildfire risk mitigation for residents that rent or do not own the space in which they live or work should also be considered. This may require tailored communications with property owners for homes and offices.

C.2.3. How can wildfire-resilient infrastructure design better address equity and climate justice?

Building on the discussion in question 2, many participants emphasized the importance of doing more work to address vulnerable housing types, such as manufactured homes, and to support lower-income individuals who struggle to rebuild following wildfire damage. For example, individuals who live in rentals, apartment complexes, or mobile home parks often do not have the ability to address wildfire mitigation strategies if their landlords are uninterested or unwilling to make the investment. It can be disempowering to be presented with information on mitigation techniques but unable to implement them. Destructive wildfires can contribute to the housing crisis, as many lower-income individuals may be unable to rebuild due to lack of funding, insurance issues, and permitting challenges.

Participants also emphasized the importance of ensuring an equitable approach to developing risk reduction strategies. For example, in Wenatchee, Washington, the city is partnering with existing cultural and religious groups in the community to deploy communication partners. Wenatchee prioritized listening to overburdened and underrepresented communities and understanding their needs before developing risk reduction strategies. Although this kind of work can take a significant amount of time and requires building trust in communities, it is essential for establishing a foundation with vulnerable groups and developing equitable solutions.