Scaling and Application of Climate Projections to Stormwater and Wastewater Resilience Planning

pathways
CLIMATE INSTITUTE

WUCA
Water Utility Climate Alliance

WUCA STORMWATER / WASTEWATER COMMITTEE

Alan Cohn (Committee Co-Chair)
Miranda Cashman
New York City Department of Environmental Protection

Julia Rockwell (Committee Co-Chair)
Tsega Anbessie
Philadelphia Water Department

Joe Smith
Rachel Chisolm
City of Austin

Laurna Kaatz
Denver Water

Seevani Bista
Goldamer Herbon
San Diego County Water Authority

David Behar
Anna Roche
San Francisco Public Utilities Commission

Ann Grodnik-Nagle
Miles Mayhew
Seattle Public Utilities

Tirusew Asefa
Tampa Bay Water

Suggested Citation

Finzi Hart J, May CL, Mak M, Ramirez-Lopez D, Cohn A, Rockwell J, Anbessie, T. 2022. Climate Projections for Stormwater and Wastewater Resilience Planning.

LEAD AUTHORS

Juliette Finzi Hart
Christine L. May
Michael Mak
Daisy Ramirez Lopez
Yanna Badet
Pathways Climate Institute

Alan Cohn (Committee Co-Chair)
New York City Department of Environmental Protection

Julia Rockwell (Committee Co-Chair)
Tsega Anbessie
Philadelphia Water Department

ADDITIONAL ACKNOWLEDGMENTS

Thank you to Michael Wehner, Lawrence Berkeley National Laboratory and Susan Leal, Urban Water Works for their peer reviews of this report and their unwavering commitment to support the critical translation of research-based climate science to actionable science to inform decision making. Thank you to all the WUCA members and individuals who participated in interviews, answered questionnaires and surveys, and participated in WUCA's Solutions Room at the National Adaptation Forum.

We would also like to thank the individuals that contributed materials and information to support the Case Studies, including Tsega Anbessie, CJ Bodnar, Paul Galeno, Ann Grodnik-Nagle, Ruby Leung, Miles Mayhew, Alexander Mockos, Anna Roche, Julia Rockwell, Justin Twenter, Keith Ward, Michael Wehner, and David Wood.

Thank you to Lindsay Luchinsky and Katie Riles for help in development of the WUCA Survey Dashboard.

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Map of water utilities that participate in the Water Utilities Climate Alliance

INTRODUCTION

Water, wastewater, and stormwater utilities in the United States - and throughout the world - recognize that a changing climate means changing precipitation, storm, and flooding patterns. Utilities also recognize that they must account for these changes in current and future projects. The Water Utility Climate Alliance (WUCA) brings together 12 of the nation's largest water providers to leverage their collective expertise, advance climate change adaptation, planning and decision-making, and support the development of leading practices that are actionable, equitable, and a model for other water utilities. The success of WUCA's mission and actions has brought together the companion wastewater and stormwater utilities of the 12 member agencies, with a goal of identifying best practices, lessons learned, and barriers associated with the use, scaling, and application of climate projections, with an emphasis on future extreme precipitation. While water utilities must consider the impact of climate change on long-term water supply and demand, wastewater and stormwater utilities (herein after referred to as utilities) must consider how to adapt to changing performance standards, regulatory drivers, and flooding impacts as extreme storms become more intense and back-to-back or compound events become more frequent under a warming climate.

Many of the WUCA member utilities are actively planning for future climate regimes and related impacts to their systems. Yet, there is no consistent federal guidance or regulatory mandates that require utilities to use forward-looking climate modeling and information in their planning. As a result, each agency typically uses their own methods to prepare for future risk, based on their own analyses and available climate science, and their own leadership directives. WUCA members solicited this study with the goals of:

- **Identifying best available methods and tools** for utilizing historic data and future precipitation projections
- **Summarizing best approaches** in use or under development related to future extreme precipitation events
- **Characterizing the major challenges** related to using future condition precipitation projections
- **Highlighting successful approaches and lessons learned** related to using future precipitation projections
- **Documenting the outcomes** in an easy-to-read report that summarizes the elements above
- **Recommending next steps** to close data gaps

The research team developed a full literature review and accompanying matrix that provides key insights into each document and resource reviewed, four practitioner case studies, two research case studies, and a dashboard that summarizes initial results of a national survey. These resources are available on the WUCA website. This report provides an executive summary of the findings from each of these project components and synthesizes these findings through a summary of observations and recommended next steps.

Header photograph courtesy of Jim Gade, Unsplash

LITERATURE REVIEW

Understanding how climate change will impact the earth's water cycle is a vital and active area of research for climate scientists, hydrologists, resource managers, modelers, and many more. With every advancement in global climate model simulations, researchers work quickly to incorporate these new outputs into scientific applications aimed at improving our understanding of how the warming climate will alter or transform various aspects of the global, regional, and/or local water cycles. Journals overflow with articles that describe advances in understanding sea level rise, extreme precipitation, changing storm patterns, and how these various impacts compound and converge, leading to unprecedented and highly damaging storms and floods. The breadth of research on the water cycle and climate change can seem daunting for someone not immediately steeped in the research community, and sometimes even for those within it.

At the same time, engineers, practitioners, and industry leaders forge ahead with existing information to manage stormwater and wastewater systems that, in many instances, are aging and often not equipped to effectively manage today's extreme precipitation events, let alone future precipitation extremes. Utilities must ensure operations and maintenance in today's climate, while simultaneously working to prepare for the future. Equally, they must respond to competing priorities, needing to win ratepayer or tax-payer approval for investments, whose full value and benefits may not be realized until later this century when future disasters are averted.

Often, actors on the two sides of the water cycle – the academic and the practitioner-based – work in parallel, with limited opportunity for interaction or collaboration across the aisle. An initial goal of this study was to conduct a thorough, directed review of the current extreme precipitation and future storm research. This included reviewing studies and examples of how this research is translated to inform water utility infrastructure design and planning, and documenting successes, lessons learned, and current best practices. This review serves as one method to connect practitioners to emerging research.

The literature review focused on reports and guidance documents provided by the WUCA project committee, with an emphasis on the development of intensity-duration-frequency (IDF) curves and emerging research on increasing extreme storm intensity and frequency (including hurricanes on the East and Gulf coasts, and atmospheric rivers and extratropical cyclones on the West coast). The research team bolstered this initial collection with additional literature that focused on the data, tools, and methods commonly used in stormwater and wastewater infrastructure planning and design, the ability of global climate models to characterize extreme precipitation, and the associated downscaling methods used in current practice to support infrastructure design. As an active area of research, new studies have – and will continue to – come online since the original literature review. This discussion therefore provides an overview of information up to the time of this report's development (summer 2022).

Header photograph courtesy of Attila Bingol, Unsplash

The literature review also helped inform the selection of case studies, the development of interview questions, and a national survey designed to better understand and elucidate the challenges faced by utilities and their customers related to climate change and the use of projections. The full literature review and associated literature review summary matrix are available on the WUCA website. An overview of key findings and takeaways is summarized below.

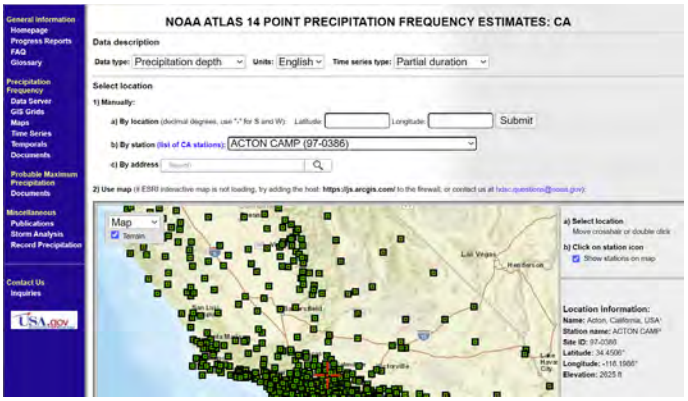
HISTORICAL PRECIPITATION

In the United States (U.S.), stormwater infrastructure is typically designed using federal, state, and local design standards and criteria based on historical precipitation probabilities; therefore, new infrastructure is often not designed to consider future climate change (Lopez-Cantu, Prein, and Samaras 2020).

Local rain gauge observations from individual weather stations, and rain gauge observations collected within managed data repositories (e.g., Applied Climate Information System[1]), are the most used historical observation data sets. Historic weather observations, often referred to as the historical record, are important for understanding current climate conditions and trends with respect to average annual precipitation and extreme events (Huang et al. 2017).

Rain gauge observations provide point-based, location-specific precipitation information that is useful for understanding temporal (time-based) variations in precipitation. Gridded data products can go one step further and provide temporal and spatial variations in precipitation (e.g., Parameter-Elevation Regression on Independent Slopes Model, or PRISM[2]). Significant research is still underway to develop improved data products, particularly gridded data products, that represent historic precipitation while preserving the intensity and spatial variability of extreme events (Pierce et al. 2021). As our understanding of the historic climate increases, and our observational records become longer, this information can be used to better inform our understanding of the future climate, amidst natural variability.

For stormwater planning, the historical record is used to understand precipitation intensity (how much rainfall falls), duration (over what length of time), and frequency (how often this pairing of intensity and duration occurs). These parameters are often displayed in the format of intensity-duration-frequency (IDF) curves. NOAA Atlas 14 – a data product that provides this information – is the *de facto* standard for designing, building, and operating utility infrastructure relative to precipitation (Ragno et al. 2018; Tetra Tech Inc. 2015; Dewberry et al. 2018, Figure 1). For stormwater utilities, IDF curves are often based directly on NOAA Atlas 14, or the NOAA Atlas 14 curves are validated or adjusted to represent local conditions using local rain gauge observations (Cheng and Aghakouchak 2014; Ragno et al. 2018; Dewberry et al. 2018).



NOAA ATLAS 14 POINT PRECIPITATION FREQUENCY ESTIMATES: CA

Data description

Data type: Precipitation depth
Units: English
Time series type: Partial duration

Select location

1) Manually:

a) By location (decimal degrees, use "-" for S and W): Latitude: Longitude:

b) By station (list of CA stations): ACTON CAMP (97-0386)

c) By address

2) Use map (If ESRI interactive map is not loading, try adding the host: https://js.arcgis.com/ to the firewall, or contact us at hdsc.questions@noaa.gov):

a) Select location
Move crosshair or double click

b) Click on station icon
☑ Show stations on map

Location information:
Name: Acton, California, USA
Station name: ACTON CAMP
Site ID: 97-0386
Latitude: 34.4506°
Longitude: -118.1966°
Elevation: 2625 ft

Figure 1. Screen capture of NOAA Atlas 14 Point Precipitation Frequency Estimates for Southern California. (Accessed from https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=ca, December 29, 2022.)

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[1] http://www.rcc-acis.org/

[2] https://climatedataguide.ucar.edu/climate-data/prism-high-resolution-spatial-climate-data-united-states-maxmin-temp-dewpoint

NOAA Atlas 14[3], a product of the NOAA National Weather Service Hydrometeorological Design Studies Center (HDSC), provides precipitation frequency information for the U.S. states and territories (Bonnin et al. 2006). The NOAA Atlas 14 frequency methodology is based on the concept of temporal stationarity, which assumes that the characteristics of extreme precipitation events do not change over time, and future climate conditions can be represented by historical observations (National Weather Service 2022; Cheng and Aghakouchak 2014). Many of the current NOAA Atlas 14 estimates are outdated and do not reflect existing conditions or storm changes even within the last several decades. Until 2022, NOAA did not have consistent budget for updating Atlas projections, which resulted in states or regions having to cost share updates for their regions. Many states therefore are working with outdated information, with some, such as the Pacific Northwest, using information that dates to the 1960s and 1970s (Figure 2).

Moreover, it is now well understood that climate conditions are not stationary, and reliance on historical assumptions about the magnitude and duration of extreme events in the future is not appropriate (USGCRP 2017; Hayhoe et al. 2018; Cheng and Aghakouchak 2014). While most extreme value analyses have sought to use as long of a historical record as possible, recent studies have shown that this practice may exacerbate the underestimation of extreme events, and that limiting the length of record to appropriately represent the current climate may be recommended in light of a nonstationary climate regime (DeGaetano and Castellano 2018).

Figure 2. Flooding in Pioneer Square, Seattle, WA. Atlas 14 precipitation projections are not available in the Pacific Northwest, forcing Seattle and other Pacific Northwest cities to plan using outdated information. (Photo courtesy of Seattle Public Utilities.)

The Federal Highway Administration tasked HDSC with examining the potential impact of nonstationary climate conditions on precipitation frequency estimates, as well as investigating methods to incorporate nonstationary climate effects within NOAA Atlas 14 (National Weather Service 2022). Although progress has been made, the National Weather Service (2022) notes that additional research is necessary to make future precipitation estimates robust enough for engineering design applications, and to streamline the analysis processes to accommodate future updates to global climate projections.

Research advancements by the Department of Defense (DoD) and the Strategic Environmental Research and Development Program (SERDP) identified increasing extreme preciptation trends (and increases in all dimensions of IDF curves) within recent decades for DoD facilities across the United States (Kunkel et al. 2020, Figure 3). Kunkel et al. 2020 found that when the atmosphere is moisture limited, extreme

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[3] https://www.weather.gov/owp/hdsc

precipitation events can only be formed by strong weather systems (e.g., frontal systems or cyclones), while an atmosphere that is more heavily saturated with moisture will easily trigger extreme events. Knowing that global temperatures will increase in the future and that moisture availability and temperature are closely linked, this is an important finding pointing to continued increases in the frequency and intensity of extreme events.

Recently passed legislation, however, addresses this challenge. The 2022 Bipartisan Infrastructure Investment and Jobs Act provides funding to NOAA that "shall be for coastal and inland flood and inundation mapping and forecasting, and next-generation water modeling activities, including modernized precipitation frequency and probable maximum studies." Referred to as Atlas 15, NOAA has committed to updating all precipitation information nationwide by 2027. Similarly, the Providing Research and Estimates of Changes in Precipitation (PRECIP) Act requires NOAA to:

- Update precipitation frequency estimates for the United States.
- Seek to enter an agreement with the National Academies of Science, Engineering, and Medicine to conduct a study on the state of practice and research needs for precipitation estimation, including probable maximum precipitation estimation.
- Consult with relevant partners on the development of a plan to update probable maximum precipitation estimates.
- Develop guidance regarding probable maximum precipitation estimates that (1) provides best practices for federal and state regulatory agencies, private meteorological consultants, and other users that perform probable maximum precipitation studies; (2) considers the recommendations provided in the National Academies study; (3) facilitates review of probable maximum precipitation studies by regulatory agencies; and (4) provides confidence in regional and site-specific probable maximum precipitation estimates.

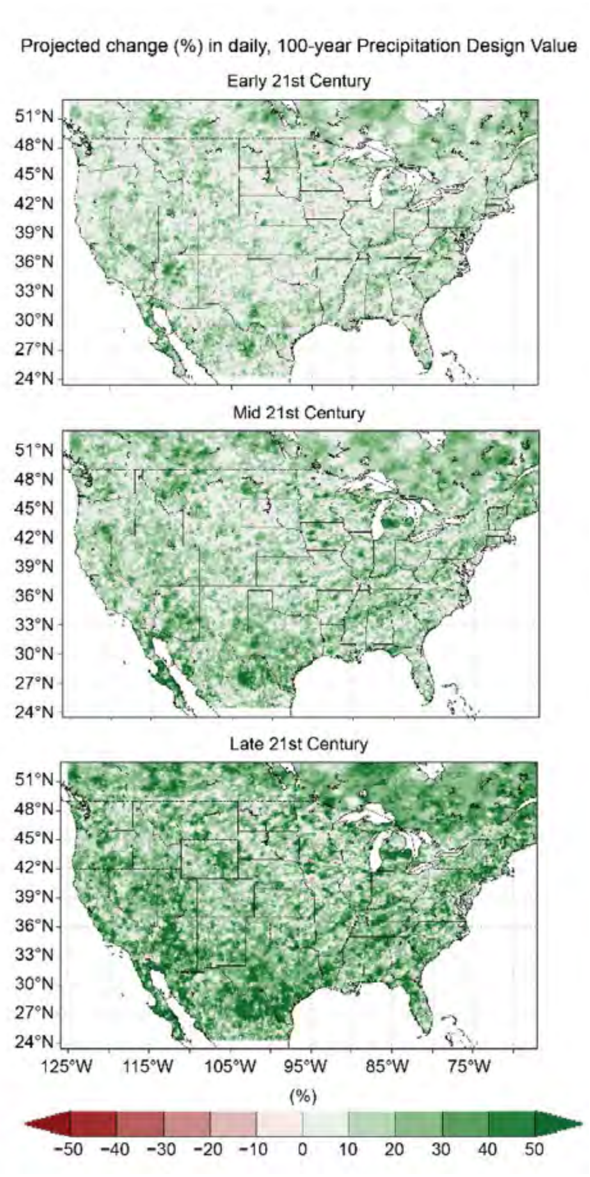

Figure 3. Projected increased in 100 yr / 5 day totals through end of century, under the RCP 8.5 warming scenario. (Images reproduced from Kunkel et al. 2020.)

FUTURE PRECIPITATION PROJECTIONS

Figure 4. Flooding in Houston, Texas, following Hurricane Harvey. (Photo attribution: urban.houstonian from Houston, TX, USA, CC BY 2.0 <https://creativecommons.org/licenses/by/2.0>, via Wikimedia Commons.)

Projections of precipitation under climate change vary considerably with geography. However, an increase in the frequency and intensity of downpours is among the clearest precipitation trends related to climate change in the U.S. and globally, and one that is expected to continue (USGCRP 2017; IPCC 2021; Seneviratne et al. 2021; Reed, Wehner, and Zarzycki 2022). Rising temperatures have increased the severity of storms (because a warmer atmosphere holds more moisture), and some storm types are increasing in severity beyond existing empirical relationships. For example, the Clausius-Clapeyron relationship relates temperature increases to vapor pressure, or the water-holding capacity of the atmosphere, but, depending on storm type, short duration extreme rainfall and/or total precipitation across extreme storms are exceeding this relationship[4] (Patricola et al. 2022; Papalexiou and Montanari 2019; Patricola and Wehner 2018; Gori et al. 2022; Knutson et al. 2022; P. Pall, Allen, and Stone 2007; Risser and Wehner 2017).

Extreme precipitation events are already stressing stormwater conveyance systems and wastewater treatment facilities, and heavy precipitation can result in severe flooding, particularly in urbanized areas and in coastal communities affected by sea level rise and storm surge (Gori et al. 2022). As the intensity and severity of storms continue to increase under a warming climate, utility planners and engineers are looking for reasonable and scientifically defensible options to consider and apply future precipitation projections – particularly as they relate to future design storms and IDF curves.

Global Climate Models

Global climate models (GCMs) are one of the primary tools from which scientists can understand and evaluate how the climate has changed historically, and how it may change in the future. The 6th Coupled Model Intercomparison Project (CMIP6), developed for the most recent Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5), represents a substantial improvement over previous generations, with more models, more scenarios, new analyses, and improved methods for combining multiple lines of evidence (IPCC 2021). These improvements have enhanced our understanding of the response of the global climate system to greenhouse gas emissions, including climate extremes (IPCC 2021).

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[4] A common approximation for this relationship is that the saturation vapor pressure of air increases by 6 to 7 percent per degree Celsius increase in temperature.

Yet, modeling extreme events, in particular large-scale precipitation events, is still challenging at the global scale (Schewe et al. 2019). The horizontal grid resolution of global climate models varies from 500 km (about 310 mi) to 150 km (about 93 mi) – which is often insufficient to resolve the complex topography and physical processes within large storm systems. The current state-of-the-art climate models approach resolutions of 25 km (about 15 mi), which can broadly represent West coast atmospheric rivers, but even this spatial resolution is likely to underestimate extreme events (Wehner et al. 2021). Global climate models therefore generally underestimate changes in future extreme precipitation and their coarse resolution cannot resolve the complex atmospheric processes and topographic variations that are critical to evaluating changes in precipitation at the scale required for stormwater planning and design (Schewe et al. 2019).

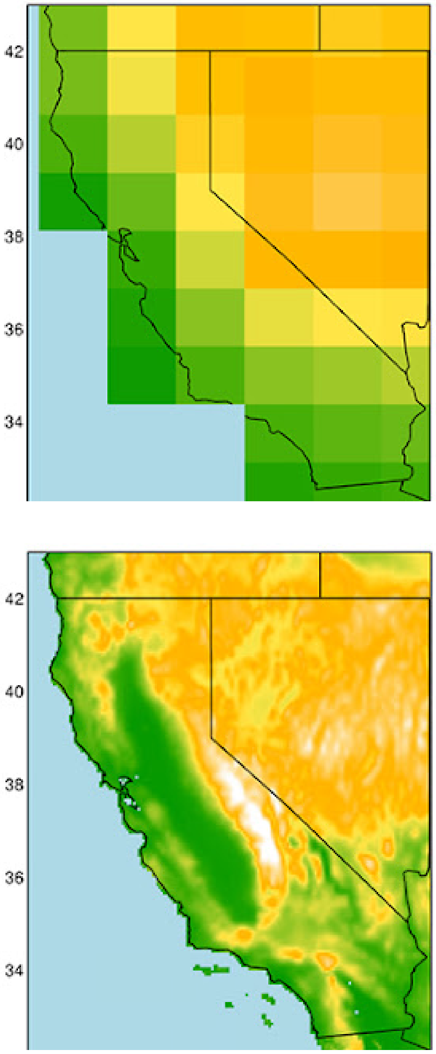


Figure 5. (Top) Demonstration of typical grid size for global climate models, often on the order 150 to 300 km. (Bottom) Image of finer resolution achieved through LOCA downscaled modeling, which helps better resolve the varied topography in California. (Images from https://calenergycommission.blogspot.com/2016/09/a-finer-picture-will-help-prepare-for.html, accessed December 29, 2022.)

To bring the resolution to a scale that is relevant for local decision-making, climate modelers can "downscale" projections from global climate models to higher resolutions. This can be done by two methods: dynamical or statistical downscaling (Figure 5).

Dynamically downscaled regional climate models can resolve climate processes that are unresolved at the global model scale (Sørup et al. 2016). A regional climate model is usually nested within a global climate model (or the global climate model provides the boundary conditions); therefore, the regional model is dynamically linked to the global model during model simulations. The resolution of the regional climate model is selected based on the size of the study area and the specific processes to be simulated and is on the order of 50 km (about 31 mi) to 1 km (about 0.62 miles). Dynamic downscaling is computationally demanding, often requiring the use of supercomputers. Because of these computational limitations, fully sampling the structural uncertainty across models is generally not possible. Currently the North American Coordinated Regional Climate Downscaling Experiment (NA-CORDEX) is the most publicly accessible dynamically downscaled dataset with spatial coverage across the majority of North America. The NA-CORDEX dataset contains 10 GCMs of various spatial resolution using boundary conditions from CMIP5 models with some output available at sub-daily time scales.

Statistical downscaling is the process by which relationships between climate models and local observations are derived, with a goal of producing localized future-condition information that is free of model bias. This approach assumes statistical stationarity, which means the relationship between historic observations and the climate models is assumed to remain unchanged over time and into the future. Because the fundamental drivers of the future climate may deviate from the historical climate, validation of the statistical stationarity ideally requires future observations which are not available, therefore back testing using historical observations allows for some insight, and is a current area of research (Dixon et al. 2016; Lanzante et al. 2018).

Statistical downscaling methods for daily precipitation are generally more challenging than for temperature, resulting in an underestimate in the representation of future extreme events. Statistical downscaling is less computationally demanding than dynamical downscaling. However, it requires long-term, high-quality observations to establish statistical relationships between the large-scale variables from the global climate models and local observations.

The U.S. Global Change Research Program adopted the Localized Constructed Analogs (LOCA) statistically downscaled CMIP5 climate projections for the Fourth National Climate Assessment (USGCRP 2017; 2018). The LOCA climate projections provide temperature and precipitation data at a 6 km horizontal resolution for 32 global climate models. LOCA attempts to better preserve extreme hot days and heavy rain events than the previous generation of downscaling approaches (Pierce and Cayan 2017). Prior to LOCA, the Multivariate Adaptive Constructed Analogs (MACA), Bias Correction Spatial Disaggregation (BCSD), and the Bias Corrected Constructed Analogs (BCCA) were commonly used statistically downscaled data sets (Tetra Tech Inc. 2015, CIRCA 2019). To date, LOCA continues to be used widely by industry professionals (Ragno et al. 2018; CIRCA 2019; Kunkel et al. 2020; Florida International University and Sea Level Solutions Center 2021; King County Wastewater Treatment Division et al. 2021).

Storylines

ONE OF THE MOST COMPELLING USES OF REGIONAL climate models, and one that will likely be useful to utilities and infrastructure planning and design efforts is “storylines,” also referred to as climate attribution and extreme weather attribution. Storylines refer to modeling specific impactful storm events that have happened, and either simulating them as they may have occurred in the past or projecting them into the future using a regional climate model. When a storm event is modeled both as it happened today (or in the recent past), and as it may have happened in a pre-industrial world in the absence of human-induced (i.e., anthropogenic) climate change, it helps elucidate the influence of climate change on the storm event, or climate attribution. When this same storm event is modeled as it could happen in a warmer world, it helps illuminate how climate change will influence future precipitation conditions. Although no storm that has already happened is likely to ever happen again in the future, the more storms that are analyzed using the storyline approach, the better our understanding becomes of the storms’ responses to climate change.

Storyline studies are often undertaken by climate scientists when storm events exceed our expectations of what is plausible. For example, heavy and prolonged rainfall in Colorado in 2013 caused severe damage and fatalities, and the storm system’s record-breaking total precipitation – and the time of year in which it occurred – were unusual (Figure 6). Climate scientists

Figure 6. Flood induced damage in Jamestown, Colorado on Sep 15, 2013 following the Boulder County flood. (Photo Credit: Steve Zumwalt/FEMA, Public domain, via Wikimedia Commons)

and statisticians spanning three organizations analyzed the storm event as it happened in 2013, compared with a pre-industrial world, and found that the total precipitation that fell during the storm event exceeded the Clausius-Clapeyron relationship (Pardeep Pall et al. 2017). They found that human-induced climate change since pre-industrial times resulted in a 30% increase in the 2013 storm's precipitation intensity, which was a 21% increase above the ~9% theoretical limit based on the Clausius-Clapeyron relationship applied to the storm conditions.

Climate attribution studies can now be generated within days to weeks of occurrence for selected extreme events. For example, shortly after Hurricane Harvey deluged Houston, Texas, in August 2017 with record rainfall, scientists released reports and peer-reviewed articles suggesting that the total precipitation that fell over Houston was likely increased by 18% to 37% due to the warming that had occurred since 1950 (Risser and Wehner 2017). As more storyline climate attribution studies are completed, both in response to extreme events and to support ongoing research efforts such as the US Department of Energy (DOE) projects Calibrated and Systematic Characterization, Attribution, and Detection of Extremes (CASCADE), HyperFacets and ICOM (Integrated Coastal Modeling) (see HyperFacets and ICOM case studies) this wealth of information can support climate science communication efforts. They can also inform future condition IDF curves and other data products to more appropriately consider a future, nonstationary climate.

Model Validation

Statistically downscaled global climate model precipitation projections from multiple sources have been tested as a validation check (CIRCA 2019; Florida International University and Sea Level Solutions Center 2021) and also compared to dynamically downscaled projections (Ragno et al. 2018; Florida International University and Sea Level Solutions Center 2021). In developing future IDF curves, some studies compare historical performance (e.g., spatial patterns) across downscaled datasets and select the best dataset to derive IDF change factors (Ragno et al. 2018), while others take an approach of developing IDF change factors for multiple datasets with supplemental guidance to select the best dataset depending on project needs (Florida International University and Sea Level Solutions Center 2021).

Common end products include future IDF change factors which can be applied to NOAA Atlas 14 historical IDF curves to scale to future time periods, or updated future IDF curves (Degaetano and Castellano 2014; Aghakouchak et al. 2018; Ragno et al. 2018; Kunkel et al. 2020; Florida International University and Sea Level Solutions Center 2021; Miro et al. 2021). IDF change factors derived from downscaled global climate model projections are also typically applied to historical data such as observed gauge data (PWD and CDM Smith 2020).

Online tools with interactive dashboards have begun making future precipitation projections more accessible. Conveniently, these tools often provide pre-calculated IDF curves for a specific region, effectively reducing process time and resource needs for utilities. These tools also offer documentation and relevant reports that provide further information on methodologies, data input, and other resources. Example of dashboards are the Mid-Atlantic Curve Tool (see also Chesapeake Stormwater Network Case Study)and the Computerized Tool for the Development of Intensity-Duration-Frequency Curves under Climate Change.

A current problem with scaling IDF curves to future conditions is the temporal resolution of interest (shorter durations, e.g. hourly or even sub-hourly) for urban flooding. Some studies either limit the publication of future IDF curves to the daily duration (Dewberry et al. 2018), apply a temporal downscaling step (e.g., sub-daily adjustment factors or quantile mapping) based on historical relationships (Degaetano and Castellano 2014; Tetra Tech Inc. 2015), or uniformly scale across a range of temporal durations (Ragno et al. 2018; Florida International University and Sea Level Solutions Center 2021). While Ragno et al. 2018 and Florida International University and Sea Level Solutions Center 2021 demonstrate that scaling factors for both sub-daily and daily duration would be similar, this practice may not be appropriate where shorter duration versus longer duration events are changing differently in a warming climate (Patricola et al. 2022, see also San Francisco's Extreme Precipitation Study Call-out Box).

Ultimately, the use of LOCA, or other downscaled climate projections, to produce future condition IDF curves has become almost standard practice today. However, when developing actionable tools like IDF curves, users must decide whether to use one or multiple LOCA grid cells, as well as the full suite or a subset of the available climate models. These decisions can ultimately affect the value and utility of the IDF curves for a particular agency or location, as different choices can yield potentially different results (Lopez-Cantu, Prein, and Samaras 2020; Fowler, Blenkinsop, and Tebaldi 2007).

In practice, the global climate models and their downscaled counterparts should not be used blindly, and care should be taken to select the suite of models that characterizes the historical climate and the climate variability of the region of interest at both temporal and spatial scales. The use of multiple global climate models (an ensemble) can help bracket the range of potential changes or better characterize future uncertainties (Seattle Public Utilities (SPU) 2017; Ragno et al. 2018), see also SPU case study. In many cases, no publicly available climate change data product may be found to be "fit for purpose." While customized calculations may be informative in these cases, expert judgement should always be used in the interpretation of climate change information.

LITERATURE REVIEW KEY TAKEAWAYS

EVEN WITH THE PREPONDERANCE OF STUDIES AND LITERATURE ON THIS TOPIC, analysis of how storms will change continues to be an active area of research. Challenges remain in scaling IDF curves for storms with shorter durations. Moreover, guidance, whether at the federal or local scale, still often relies on information based on past storm events, and assuming a stationary, or predictable and unchanging, storm regime in the future (Lopez-Cantu, Prein, and Samaras 2020). Equally, there is a vital need for a more comprehensive update to NOAA Atlas projections to better address a future nonstationary climate. The recent funding through the PRECIP Act and the Bipartisan Infrastructure Investment and Jobs Act, presents a timely opportunity to ensure that Atlas 15 considers non-stationarity of the future climate for its updated projections.

Consistent approaches and guidance from federal and state levels, with more emphasis placed on ensuring that NOAA Atlas 15 addresses a future, nonstationary climate, could have a profound impact on U.S. infrastructure planning and design. Indeed, one provision of the PRECIP Act is to develop this type of guidance; it will be important to include the input from SW/WW utilities to ensure that their data and planning needs are considered and addressed.

There remains a critical data gap between climate modeling in the research and academic sectors, guidance from authoritative sources, and the practical use of this information by planners, engineers, and decision makers. Including a translator, or someone who can speak both to the science and the engineering, builds trust between both parties by ensuring that both understand the other (see also San Francisco Extreme Precipitation Study Call Out Box). Creating a platform for continued dialogue between utilities and academic/scientific research efforts is critical, particularly if additional scenarios or analyses are needed to transform these research efforts into actionable science for planning and design.

San Francisco’s Extreme Precipitation Study

The San Francisco Public Utilities Commission (SFPUC) partnered with Lawrence Berkeley National Laboratory (LBNL) and Pathways Climate Institute (Pathways) to fill a critical data gap for the City of San Francisco and the San Francisco Bay Area – understanding how extreme storms may change under a warming climate. This research collaboration leveraged funding and support from multiple city agencies including SFPUC, Port of San Francisco, San Francisco Airport, and the Office of Resilience and Capital Planning. Each agency had a vested interest in better understanding future extreme precipitation, and the findings would ultimately support the SFPUC’s sewer system improvements, the Port’s Waterfront Resilience Program, the Airport’s flood management system, and Climate SF, the City and County of San Francisco’s unified program to enhance climate resilience.

Six historic large-scale storm events were modeled under existing and future conditions using the Weather Research and Forecasting (WRF) mesoscale climate model with a 3-km grid cell size resolution over the Bay Area to adequately define local topography and convective scale precipitation processes. The study assessed the response to anthropogenic warming across the storms and how Clausius-Clapeyron temperature-precipitation scaling will change over shorter and longer durations within the region. These findings were reviewed by an external scientific peer-review panel and published by Patricola et al. (2022) under the title “Future Changes in Extreme Precipitation Over the San Francisco Bay Area: Dependence on Atmospheric River and Extratropical Cyclone Events” in an internationally recognized journal, *Weather and Climate Extremes*.

The study found that changes in storm-total precipitation depend strongly on storm type, with precipitation associated with an atmospheric river accompanied by an extratropical cyclone, the Bay Area’s most common storm type (Zhang et al., 2019), projected to increase by up to 1.5 times greater than the theoretical Clausius-Clapeyron relationship (Patricola et al., 2022). Storm-total precipitation could increase by up to 26 to 37% in 2100 relative to historical. This level of increase is not represented within the current statistically downscaled climate projections, such as LOCA. The changes in the shorter durations may exceed these changes, posing challenges for infrastructure planning and resilience (Ayat et al., 2022).

A multi-agency stakeholder group met regularly as the work progressed to promote consistency in how the City would frame and use the research findings. It is critically important that the findings are translated into actionable science to inform decision-making. This led to the development of a two-part guidebook to inform decision-makers (Volume 1) and practitioners and technical staff (Volume 2) as they make scientifically informed decisions (to be released in 2023). The outcomes of both volumes, including future Intensity-Duration-Frequency precipitation estimates and visualizations of future atmospheric river severity, will be published in peer-reviewed scientific journals to broadcast the findings and innovative methods for the larger scientific community and industry. The collaborative partnership throughout this study highlights the importance of bridging the gap between academic / research organizations and the practical needs of utilities and other agencies. The Integrated Coastal (ICoM) and HyperFACETS projects (see Reasearch Case Study callouts) are two other large scale efforts that bridge the gap between research and industry by pairing stakeholder input with advanced modeling.

NATIONAL SURVEY

To learn about experiences and ongoing work among utilities and interested community stakeholders, the WUCA committee launched a national survey from January 20, 2021 to March 3, 2021 to learn if and how utilities are considering climate change, what information they currently use, and what barriers and challenges they and the communities they serve face. The full suite of responses are posted publicly on an online dashboard and key findings are described here.

Respondents

Two hundred four individuals, both from industry and from communities across the U.S. responded to the survey. Respondents were geographically distributed across the U.S., with several respondents from overseas (Iran, Vancouver, Sudan, Bangladesh, Figure 7). To guide respondents to questions that were most relevant to their experiences, respondents identified their role and employer. Most respondents self-identified as *community members* (37%). The next largest category of respondents were *engineers*, followed by *project managers* or *other.*

Respondents indicated they had expertise in *stormwater*, *wastewater* and *climate science*, and that they played a role in *planning and designing water infrastructure* (65%). Similarly, most respondents had experienced flooding impacts firsthand, with the majority experiencing *urban stormwater flooding and riverine flooding*, followed by *coastal flooding* and *groundwater flooding* (Figure 7).

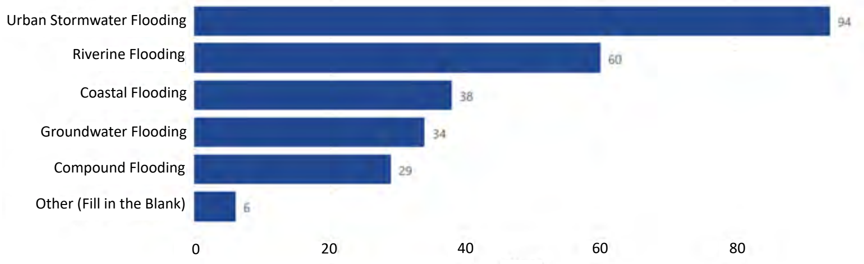


Figure 7. *(Top)* Map showing locations of survey respondents. *(Bottom)* Responses to "What flooding impacts have you experienced?"

Respondents were asked a series of triage questions designed to lead them to more in-depth questions based on their expertise and experience in engineering, climate science, decision-making, and communication. Respondents could answer yes to multiple questions regarding their area of expertise.

Header photograph courtesy of Kelly Sikkema on Unsplash

Engineering Focused Questions

Triage question: *Are you engaged in planning and/or designing wastewater/stormwater infrastructure? (n=78)*

In describing the types of hydrologic extremes observed, *atmospheric rivers* (AR) and *hurricanes* were the most observed events, followed by *extratropical cyclones*, including Nor'easters. Most respondents (63 of 78) indicated they had observed back-to-back storm events. When asked to describe which storm durations are most impactful in their region, there was considerable variability in the responses (Fig. X). A plurality (37%) identified *short-duration* (sub-daily) storms which, in urban settings, often lead to immediate impacts during extreme events, including drainage system capacity issues and localized flooding. Others indicated that *long-duration* (daily to multi-day, 29%) and *back-to-back storms* (28%), were the most impactful (Figure 8).

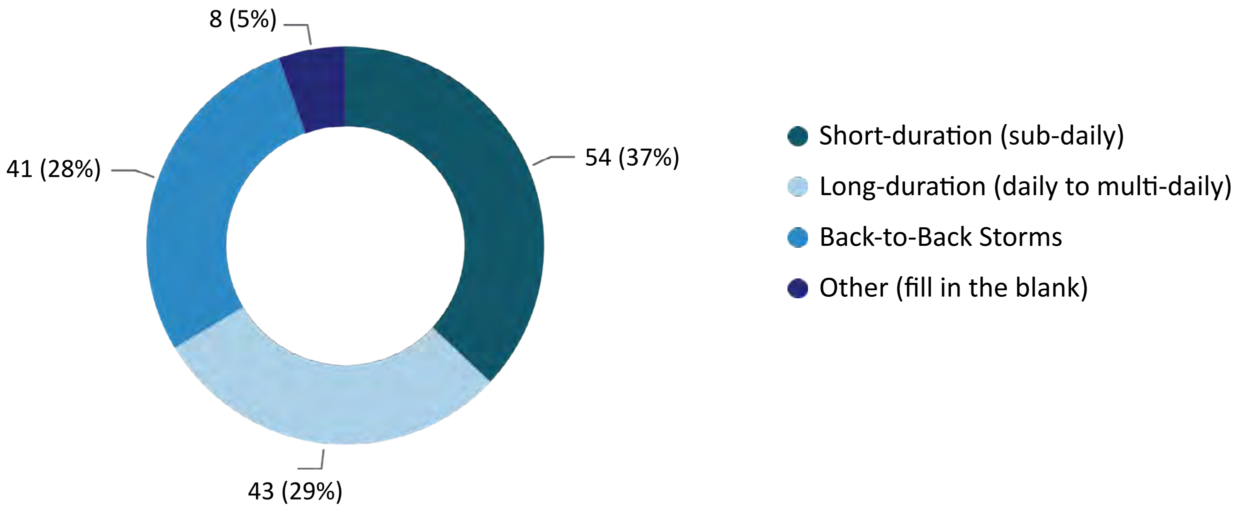


Figure 8. Responses to "Duration of hydrologic extremes that are most impactful in your area?"

Most utilities (55%) plan for a defined level of service or standard design storm, ranging from the 10-year to 100-year storm event in the planning and design of their stormwater/wastewater infrastructure. Seventy-one percent indicated that their organization used both historical and future conditions precipitation data, compared to 23% who used only historical information. However, when asked about the specific data sets, most rely on historical observations (n=65) and IDF curves (n=53) based on historical storms, compared to a smaller percentage who used future projections (n=32) and global climate models (GCMs) (n=26).

The respondents agreed with a range of different challenges and barriers to incorporation of forward-looking climate information in their work. The most identified challenge was that it is difficult to find the "best" or "right" information. The lack of regulatory drivers, combined with too many other urgent priorities were the next most identified challenges. Lack of support from leadership and lack of internal capacity were also identified as barriers.

Decision-Making Focused Questions

Triage question: *Are you engaged with climate science or future precipitation projections for wastewater/ stormwater infrastructure? (n=72)*

A substantial proportion of utilities surveyed (81%) are currently upgrading wastewater or stormwater infrastructure. Similarly, the majority indicated that climate change is an overarching part of their agency's mission, and a sizable proportion (60%) are considering future precipitation changes in their planning. When asked to describe what convinced them to consider climate change, responses included current and projected climate change impacts, lessons learned from firsthand experiences with flooding, confidence in reliable science and data, and mandates directing them to do so. Concerns about future precipitation impacts ranged from the potential for undersized flood control infrastructure, the inability to convey sewer flows to treatment plants (and provide treatment), and permit violations and water quality issues. Most (27%) are planning for the next 31 to 50 years, with fewer planning for > 50 years (25%), when climate impacts will be felt the strongest. Most respondents (35 of 72) indicated their agency had not completed a climate adaptation plan, but, of those who did, a majority (20 of 25) did consider future precipitation challenges.

Climate Science Focused Questions

Triage question: *Are you engaged with climate science or future precipitation projections for wastewater/ stormwater infrastructure? (n=77)*

In questions focused on understanding respondents' comfort and familiarity with climate science, most respondents indicated that they were familiar or somewhat familiar with climate science and future precipitation projections. Sixty-one percent of respondents said they do use future precipitation projections to inform level of service or design standards, while 39% said they do not. Of those who do, the majority (10 of 13) indicated that they were *confident* or *somewhat confident* in the information they are using compared to only 3 of the 13 who were *very confident* in extreme precipitation projections.

When asked if they think future precipitation projections are robust enough to use in their work, most (61%) replied that precipitation information was *useful sometimes*, but it depended on what science was used and how. This is in comparison to 27% who believe that projections are absolutely critical to infrastructure planning (Figure 9). Those who did not think future projections were robust enough for planning and design cited lack of standards in methodology, lack of decision-maker support, and potential for higher costs without enough justification.

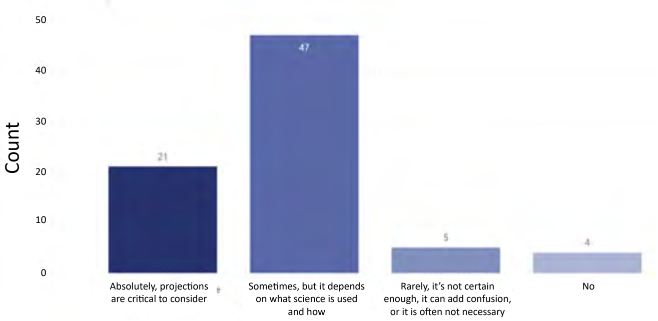


Figure 9. Responses to "Do you think future precipitation projections are robust enough to use in infrastructure planning?"

A plurality of respondents (47%) said they worked with climate science research organizations. They partnered with these organizations for dynamical downscaling and bias correction for local scale projections, updating IDF curves, and water resource forecasting, along with assessing vulnerability.

Communication Focused Questions

Triage question: *Are you engaged in communicating information about public infrastructure systems? And do you communicate climate change information to the public? (n=48)*

Ninety-one percent of respondents indicated that decision-makers in their organizations support climate resilience efforts. Sixty percent indicated that climate change information is considered important and useful in their organizations, while 33% noted that it was not fully considered yet. Respondents (85%) believed that climate change is important to their respective communities and most (81%) say their organizations are communicating about their work to prepare for climate change. When asked about how climate change uncertainty impacts decision-making, 19 of 48 survey takers indicated that it leads to action, while 9 said it delayed action. Thirteen indicated that it leads to careful planning, while only four noted that it leads to inaction.

COMMUNITY SURVEY

Of respondents who identified as community members (n=81), 57% identified as *interested community member/customer.* Twenty-one percent identified as *academic/scientific*, 9% were *public official/ community representative*. The remaining 9% identified as other.

All respondents were concerned about climate change. Many had experienced flooding in their neighborhood (or street) or in their basement or first floor, but some had not experienced flooding at all. Of those who had experienced flooding in their neighborhood or street, the most common impact was *street closure*, followed by *damage to home or property* (Figure 10). Seventy-four percent of respondents were *concerned* or *very concerned* about a future flood event, but most believed that their community/ utility was only *a little prepared* for the next big storm. Only one respondent felt they were *very prepared*. Despite the utilities indicating that they message their climate resilience efforts to the public, community members are still concerned and less certain that they will be protected under future climate conditions.

When asked to describe what improvements could help reduce flood impacts, answers ranged from *structural/physical solutions*, such as cleaning out stormwater drains regularly, updating aging infrastructure, using nature and nature-based features to create resilience, and increasing ground cover permeability. They also identified *non-structural solutions* such as limits or regulations on development and improved forecasting and climate projections.

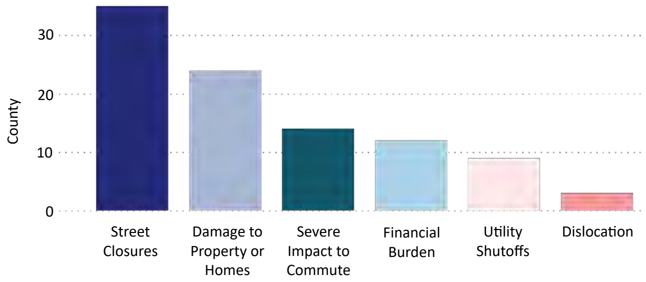


Figure 10. Responses to "How impacted were you impacted by flooding from storms in yuor home and neighborhood

In summary, these initial survey results indicate that utilities recognize the need to prepare for future storms under a changing climate. Whether due to firsthand experience with impacts of extreme precipitation and climate change, or from increased understanding of climate projections, engineers and decision-makers recognize the importance and need for using climate projections in stormwater / wastewater infrastructure planning and design. While there is growing confidence and familiarity with climate science, a lack of confidence in using these projections is not necessarily due to the level of uncertainty intrinsic to climate science but rather due to concern that they (practitioners) are not using the "right" or "best" science.

While some organizations indicated they work with climate science research organizations, others do not. As discussed in the literature review section, there is no shortage of research underway. It would be helpful to better understand why these partnerships are not more common and how best to incentivize coordination between those producing the science and those using the science. This could help build a deeper sense of trust and understanding of how the projections are developed, in turn leading to increased uptake of the more sophisticated, forward-looking climate projections.

Several science needs can be gleaned from the responses thus far. Precipitation projections for both short and long duration events are needed. Dense urban areas may see immediate impacts from short bursts of precipitation (i.e., less than 24 hours), while others with larger contributing watersheds may experience the worst flooding during longer duration events. Utilities that experience impacts from long duration storms in one season can also experience impacts from short duration storms in the next. Many regions are also facing impacts from back-to-back storm events. This could lead to changes in utility planning and design, where designing for a single discrete storm event (e.g., 10yr, 24hr) is no longer sufficient. Back-to-back storm events can lead to conditions where the second (or third) storm impacts a system that is already stressed beyond its capacity, leading to unforeseen and potentially catastrophic impacts. Utilities that use hydraulic and hydrologic computer models to inform operations and project design require design storms or longer-term timeseries as inputs.

Further research into how impactful storm types (e.g., atmospheric rivers or nor’easters) will change in size and frequency over time is also needed. Understanding shifts in storm characteristics and timing across seasons will help utility managers adapt to a new climate. While this summary focuses on precipitation, most utilities face impacts from multiple hazards. Flooding from back-to-back extreme precipitation events with long durations in the spring will be worsened by earlier local snowmelt from hotter temperatures. Increasing frequency of atmospheric rivers combined with extratropical cyclones that bring elevated coastal storm surge will further compromise sewer system capacity and asset operations, resulting in increased discharge permit violations.

CASE STUDIES

In addition to the literature review and the practitioner and community surveys, the project team developed four practitioner case studies of utilities across the U.S., at various scales of planning and implementation, to demonstrate the breadth of different methodologies, successes, and lessons learned. This report also describes two research-based case studies and discusses how these studies can support decision-making.

Given the paucity of literature or resources that clearly document data and methodologies to allow other practitioners to easily replicate successful efforts, these case studies provide a valuable tool for encouraging peer-to-peer learning. Sharing field-tested practices, which describe successful solutions as well as unsuccessful attempts, helps the entire field advance. Moreover, climate models are theoretical projections of the future; it is only when practitioners attempt to use this information, highlighting what types of outputs are useful, and which are not, that a bridge can be built between climate scientists and engineers. Practical applications of climate modeling can, in turn, inform climate modelers to encourage development of future outputs that can continue to inform future planning.

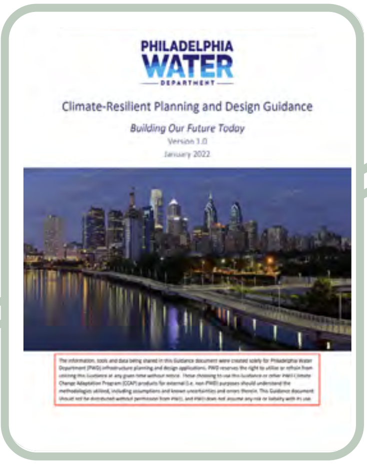
These case studies were developed following a structured interview with each utility, supplemented by a review of documents related to the utilities' efforts. The full case studies provide a detailed narrative overview of how the utility addresses climate change in their planning and design, as well as detailed descriptions of the model projections used, barriers and challenges overcome, the final application and outcomes, and the lessons learned (see Appendix A and the WUCA website). This report includes a high-level summary and lessons learned for each case study.

Flooding in Alameda County, CA, on December 31, 2022, the day this report was finalized. Rain from an atmospheric river soaked the San Francisco Bay Area, with accumulations surpassing the 6 hour, 100-year storm. (Photo courtesy of Kris May.)

Header photograph courtesy of Seattle Public Utilities

Philadelphia Water Department

Transforming Global Climate Model Precipitation Output for Use in Infrastructure Planning and Design Applications



PHILADELPHIA WATER DEPARTMENT

Climate-Resilient Planning and Design Guidance

Building Our Future Today

Version 1.0

January 2022

Summary

Philadelphia Water Department (PWD) led an initiative to develop guidance based on in-depth analysis of climate projections. The Guidance is informing a department-wide revamp of standards and criteria for resilience planning.

The Challenge

While statistically downscaled global climate model (GCM) precipitation output is available for Philadelphia, the temporal resolution is too low for direct use in model-based urban stormwater applications and GCM output for Philadelphia does not accurately represent local storm intensities and durations. In addition, there were challenges related to climate risk planning at PWD given the evolving science and lack of a regulatory driver.

The Approach

To address the challenges, PWD completed a study (Maimone et al. 2019) that used an innovative approach to transform GCM output into actionable science that can directly inform planning, design, and engineering applications, including hydrologic and hydraulic (H&H) modeling and intensity-duration-frequency (IDF) curve development. The approach uses GCM output for current (1995–2015) and future (2080–2100) conditions under the Representative Concentration Pathway (RCP) 8.5 greenhouse gas emission trajectory to develop delta change factors based on season and storm size. These factors were then used to create a plausible future hourly time series. A stochastic generator was used to explore potential variability in projected precipitation patterns to better understand the range of uncertainty. The approach used is practical and transferable, addressing the need for locally relevant and actionable climate change information in the field of water resource management.

The Outcome

The climate projections and planning recommendations are captured in the first iteration of the PWD Climate-Resilient Planning and Design Guidance (January 2022), the culmination of the effort. The Guidance provides staff across multiple departments with the information and tools necessary to make decisions in the face of uncertainty and to include forward-looking climate risk information in all planning and design efforts, including those related to structural and non-structural systems. Official PWD policy requiring use of the Guidance in infrastructure planning and design efforts, to the extent feasible, was adopted in January 2022.

Practical Applications

Several projects have been informed by the Guidance since its release, including PWD stormwater and wastewater drainage system projects, a Water Pollution Control Plant (WPCP) effluent pump station design, and planning associated with raw water pump stations at risk of riverine flooding during extreme rainfall events.

Lessons Learned

1. Do not let perfect become the enemy of progress and focus on actionable information

In developing the Guidance document, PWD accepted that there will always be uncertainty associated with climate projections and developing a singular and 'certain' projection is not practical or feasible in a field that is based on continually evolving science. The important aspect is to gain agreement that there is enough certainty in the projections to use them for making decisions and recommendations. To better understand what uncertainties do exist and how science can be made actionable, PWD recommends prioritizing engagement with federal agencies, like NOAA and NASA, as well as climate scientists from the academic community and National Labs.

2. Involve staff early and continuously on climate change related discussions; identify and rely on climate champions

PWD recognized the importance of involving staff from the beginning. This program began in 2014 by engaging staff (with a survey reaching multiple units and programs) to understand their impression of PWD's primary climate change vulnerabilities. The feedback gathered helped to identify the climate-related consequences associated with various climate impacts, including increasing precipitation. When developing the Climate-Resilient Planning & Design Guidance, staff provided input and review of the content at multiple points in the development process (for example, PWD's Climate Change Adaptation Program - CCAP - asked the questions: What tools would be most helpful? What output format would support your work? What hesitations do you have in terms of using this information and how can we help address those?). CCAP also worked to identify and develop relationships with 'climate champions' in various programs throughout the Department.

3. Stress that climate change is happening here and now

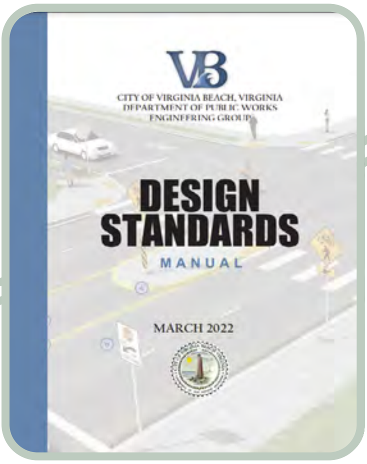
When it came to generating support and buy-in, PWD learned the importance of highlighting that climate change is happening here and now by drawing focus to recent extreme events. For example, in engaging with Executive Staff on the Guidance and the need for a department-wide policy, CCAP highlighted the devastating local impacts of Hurricanes Isaias and Ida, and the fact that climate change will make these extreme events more likely. Based on these recent events, it is already evident that PWD needs to account for increasing storm intensities and climate projections in infrastructure planning and design.

4. Top-down directives are needed to empower staff

PWD used a 'bottom-up' approach to develop the Guidance document and gain staff buy-in, but ultimately top-down directives (e.g., a new policy) were needed to empower staff to use climate projections in their work and support the consistent application of the information in existing and long-standing programs/processes.

City of Virginia Beach, Department of Public Works

Developing Future Precipitation Projections and Design Standards



Summary

The City of Virginia Beach commissioned a study to assess changes in historical and future extreme precipitation in response to heavy flooding events. The study, which received a third-party review, resulted in updates to the Department of Public Works Design Standards Manual (2020), including new requirements and design parameters for stormwater management. The effort also included an assessment of sea level rise and the potential for combined flooding impacts from extreme precipitation and storm surge events.

The Challenge

The best available precipitation information for Virginia Beach in 2016 was NOAA Atlas 14, which is baselined to the year 2000 and does not consider future climate change. A review of two long-record rain gauges showed that the NOAA Atlas 14 10-year rainfall event is about 7 to 10% below local observational data, and it was not representative of the extreme precipitation during the 2016 hurricane season.

The Approach

In 2015 the city began an initiative called Sea Level Wise to evaluate sea level rise and flood risks. In response to the 2016 flood events, this was extended to include analyses of historical and future extreme precipitation projections. The observational trend showed an increase of 3 to 7% per decade for the 10-year event, and future projections suggested additional potential increases of 7% for RCP4.5 and 24-27% for RCP8.5 by 2060 (relative to the year 2000). Using a combination of the historical trends and future projections, the city recommended the use of a 20% increase in extreme precipitation by the year 2060, assuming a 40-year lifecycle for infrastructure projects.

The Outcome

The Design Standards Manual updates included design standard changes to address future precipitation estimates, recurrent flooding, and sea level rise risks. The updates also required using this information in the City's Storm Water Management Model (SWMM). The City is continuously updating their SWMM model to better represent the stormwater system, and these updates, combined with the future precipitation updates, have allowed the City to be proactive in their efforts to reduce flood risks.

Practical Applications

Projects are designed using the revised design guidelines. Per these guidelines, engineers must increase the NOAA Atlas 14 design storm rainfall depths by 20% and must use dynamic modeling (SWMM) to analyze the pre- and post-development conditions, except for areas less than 20,000 sq. feet (PWDSM, Section 8.3.b).

The City of Virginia Beach uses the updated design storms in the Master Drainage Model which includes the Primary Stormwater Management System for the majority of the city. This model allows the City to identify the areas of greatest risk and prioritize projects to reduce flood risks.

Lessons Learned

1. Confirm and identify the question at hand
It is important to confirm the questions to be answered and the desired outcomes (e.g., updates to design standards) from the outset to help streamline the process and gain agreement across multiple parties.

2. Use best available science and data
The City relied on multiple rain gauges, used the best available data, and clearly documented their analysis approach and results. This allowed two independent third parties (Virginia Department of Transportation and the Transportation Research Council) to review and validate the methods and findings. This provides confidence in the process.

3. Do not wait, get started
These studies and the corresponding updates to existing design standards can require multiple years for planning, analysis, and implementation. The most difficult step is getting started. Waiting for the “most up-to-date” data impedes advancements.

4. Rely on regional efforts
The City of Virginia Beach benefited from a series of “green light” situations that eased the entire process (from analysis, to adoption, to implementation). There was sufficient budget, political support, and staff capacity to move this effort forward. However, the City recognizes that this is not always the case. Under alternative circumstances, the City could have waited for a regional effort to be completed to inform similar updates.

Figure 11: Flooding along a street in Virginia Beach. (Photo courtesy from Virginia Beach Fire Department.)

Seattle Public Utilities and King County

Ship Canal Water Quality Project – Combined Sewer Overflow Program – Preparing for Extreme Rainfall with Climate Ready Design

Ship Canal WATER QUALITY PROJECT

Seattle Public Utilities

King County

Project Overview

Investing in the Health of the Sound and the Future of Our Region

How we're working with the community

Contact

Summary

Seattle Public Utilities' (SPU's) Ship Canal Water Quality Project used both observations of increased precipitation and overflows with modeled future extreme precipitation projections to inform the design of a 2.7-mile-long storage tunnel to manage combined sewage and stormwater overflows into the future.

The Challenge

The Ship Canal Water Quality Project's design began in 2013 with an expected completion date in 2025. Taking climate change into consideration, initial designs included a 6% scaling factor to account for potential future precipitation increases. This scaling factor was selected based on early model projections that suggested a 0 – 15% increase in extreme precipitation by the end of century. However, the combination of heavy rains in 2015 and 2016 and improvements in climate modeling, specifically related to extreme precipitation projections, suggested that the 6% scaling factor would not be adequate to prevent future overflows.

The Approach

SPU and King County considered several options before deciding on the underground storage tunnel. Alternative options included green infrastructure and local detention facilities. Overall costs were similar, but the tunnel resulted in fewer impacts to nearby communities and greater operational flexibility.

The initial design phase considered a 14-foot (ft) diameter storage tunnel. To support the project, SPU updated its rainfall statistics using historical data and future precipitation projections. The preliminary results revealed that observed precipitation trends showed that current precipitation values had already increased more than the 6% assumed to account for future increases. These results were consistent with similar analyses completed by King County, as well as observations from 2015 and 2016.

The Outcome

The Ship Canal Water Quality Project storage tunnel size was increased in diameter from its original design of 14 ft to 18 ft 10 inches (in), to capture the expected increase in stormwater volume (Figure 12). The upsizing of the tunnel from a unique diameter (14 ft) to an industry standard size (a size often used for transportation tunnels) also minimized additional capital cost. The larger diameter design increased the tunnel storage volume from ~15-million gallons to about 30-million gallons with only $30 million in additional costs.

Practical Applications

The engineers' in-depth knowledge of existing performance issues paired with improved existing and future condition precipitation analyses led to concerns about the initial proposed tunnel size. SPU and King County made the decision to upsize the tunnel. With leadership on board, and community support for the larger project, the project moved forward with the larger storage volume design.

Lessons Learned

1. Communicate uncertainty as part of the performance standard to support decision-making.
Rather than rely on a single, set number that may prove incorrect in subsequent years, SPU and King County engineers recognized the value of explaining the range of uncertainty to decision-makers relative to meeting performance standards. If a solution provides a 70% certainty of meeting a performance standard in the future, and decision-makers request an increase to 80 to 90% certainty, overall agency support and buy-in increases. Communicating uncertainties clearly and in a relevant metric can be a powerful tool and can help manage expectations about future changes (e.g., updated science) that could occur later in the design process.

2. Intentionally look at the long-term resiliency of a project.
With hindsight, project team members indicated more robust analysis of observed and future precipitation should have occurred at the beginning of the project. They indicated that the initial approach of applying the average scaling factor of 6% across the lifetime of the project was too simplified and didn't fully account for changes in future condition extreme events. In retrospect, project leads indicated that had they looked at more extreme future scenarios, they may have recognized the increased resilience a larger more-standard diameter tunnel could provide, without a proportionate increase in cost.

3. Climate change is one of many factors influencing project design.
For SPU, the primary driver was regulatory compliance and understanding the potential risks that could occur in the future based on sizing facilities for historical rainfall instead of future projections. As updated science became available, the risk of potential future non-compliance increased, resulting in a design change.

4. Lack of clear climate policies can still lead to resilient decision-making.
Although policies existed for sea level rise, there were no clear policies on how to consider precipitation-related climate impacts during the design phase for this project. However, the robust analysis of future precipitation developed for this project is informing other projects. SPU is one of the most proactive City departments in integrating climate science into capital projects and operations. SPU's approaches are likely to become a model for other departments as adaptation planning and investment becomes more standard.

Figure 12: MudHoney, the 18 foot diameter Tunnel Boring Machine, will build the conveyance tunnel for the Ship Canal Project. (Image from: https://spushipcanal.participate.online/, accessed December 29, 2022.)

Chesapeake Stormwater Network

Developing a Regional Resilience Framework

Summary

The Chesapeake Stormwater Network (CSN) is a regional effort to standardize stormwater practices within the Chesapeake Bay Watershed with affiliated partners. It seeks to establish best management practices (BMP) for future resilient designs that consider future climate change.

The Challenge

The current stormwater design standards for most Mid-Atlantic states is based on historic precipitation data (NOAA's Atlas 14 – Volume 2 uses observed data that is twenty years old). In many locations, the NOAA Atlas 14 IDF curves underrepresent today's climate conditions. Using outdated precipitation information, compounded by varying design and performance standards across the states and state agencies, results in reduced infrastructure performance and inadequate stormwater policies.

The Approach

CSN initiated a comprehensive review of the state of the practice across the Mid-Atlantic. This review was documented across four reports designed to synthesize climate projections and implications for stormwater design in the region. The effort included a climate survey, review of design standards, climate projections, and a BMP vulnerability analysis. For conclusions and recommendations see the Outcome section.

In tandem with CSN's efforts, NOAA's MARISA team published the online Mid-Atlantic IDF Curve Tool where projected IDF curves have been developed for multiple stations in the Bay watershed. The tool was driven by the need to evaluate climate change implications on total maximum daily loads (TMDLs) at the county level. Data inputs include station-based observations (historical data) and projected precipitation from downscaled climate model ensembles (MACA, LOCA, and BCCAv2) and regional climate models (NA-CORDEX). Outputs consist of IDF curves and future change factors. The baseline for historic data was purposefully selected to align with NOAA's Atlas 14 historical period, 1950-1999. Two future time periods, 2020-2069 and 2050-2099 (i.e., 50-year periods) are available for future projections under the RCP 4.5 and 8.5 climate scenarios.

The tool enables users to search and download individual county scale IDF curve change factors for the 2-year to 100-year storm event (for 5 minute to 7-day durations) within the Chesapeake Bay Watershed and Virginia. Updates to the IDF curves will be made using the upcoming release of the full downscaled CMIP6 archive, more recent rainfall observations, updates to NOAA Atlas 14, and/or technical advancements which improve IDF curve estimation methods.

The Outcome

Over the next three to five years, CSN expects to launch four products to advance regional consistency based on the identified challenges. These efforts will work towards more climate resilient initiatives and provide states with the necessary information to make climate informed decisions.

Practical Applications

CSN's comprehensive review revealed that several states within the Mid-Atlantic region (Delaware, District of Columbia, and Maryland) are individually working to address climate change impacts related to stormwater management and/or floodplain protection. Commonalities exist across the various state led efforts, such as completing vulnerability assessments, responding to changes in policy, and developing resources/tools.

Lessons Learned

1. Climate is nonstationary

Historical precipitation data, specifically NOAA Atlas 14 IDF curves, do not reflect today's non-stationary climate. Continued use of existing design standards will likely result in undersized stormwater management infrastructure in the future. Updating NOAA Atlas 14 will be a valuable next step for all communities. This update would increase consideration of future precipitation conditions within stormwater planning and design.

2. States and local governments need updated design standards

The findings of CSN's work highlight responses from practitioners, engineers, decision-makers, stakeholders, as well as climate-related progress in several states. Based on survey responses, there are climate change impact concerns related to both public and private infrastructure. There is also consensus on the need for updated engineering criteria and performance standards that consider future climate change.

3. Uniformity across the watershed is needed

Standards not only vary across states, but they can also differ within departments. There are often differences in how precipitation data is used and considered in planning and design. Developing uniform design criteria and performance standards would promote regional resilience and would also allow for easier sharing of best practices and lessons learned.

4. Guidance and support go beyond analytical needs

States and cities need support developing locally relevant climate projections. Climate projections must also be translated into effective and easily digestible language for decision-makers. Forward thinking decisions require actionable science that directly informs planning, design, and engineering applications. Actionable science can include both qualitative and quantitative formats and is a core facet of the CSN framework. Future tools and applications will best serve under-resourced states and localities if they are published and communicated with this in mind.

Research Case Study

Integrated Coastal Modeling (ICoM) - A multi-institutional research effort led by Pacific Northwest National Laboratory and funded by the U.S. Department of Energy

Summary

Integrated Coastal Modeling (ICoM) is a research-based effort focused on improving understanding of coastal evolution that accounts for the complex, multi-scale interactions among physical, environmental, and human systems within the mid-Atlantic region. ICoM brings together multiple modeling tools to represent both extreme events and long-term changes in human and natural systems, including land-river-ocean interactions, surface water-groundwater interactions, surface-atmosphere interactions, and large-scale drivers of extreme events. The research extends beyond understanding future extreme precipitation; however, this case study focuses on the aspects of ICoM that are most relevant for characterizing how extreme events may change under a warming climate.

The Challenge

Major gaps exist in the understanding of coastal processes, which are generally difficult to simulate in numerical models due to the presence of complex land-sea interactions and coupled interactions between human and natural systems, especially in the context of multiple interacting stresses over multi-decadal timescales. Questions remain on the moisture sources for precipitation over land surfaces (e.g., urban areas) – addressing this data gap can reduce uncertainty in precipitation storm modeling.

Partners

The project is led by the Pacific Northwest National Laboratory (PNNL) with collaborators from Penn State, University of Washington, University of Houston, Los Alamos National Laboratory, Cornell University, Rutgers, Lawrence Berkeley National Laboratory, Virginia Institute of Marine Science, University of Arizona, University of California Davis, Baylor University, and the University of Michigan.

The Approach

ICoM is funded by the U.S. Department of Energy (DOE) across four specific DOE program areas: Regional and Global Modeling and Analysis, MultiSector Dynamics, Earth System Model Development, Earth System Science. ICoM also includes cross-cutting research to address topics that are relevant across the four DOE programs.

Of the DOE program areas, the Regional and Global Modeling and Analysis (RGMA) program is the most relevant for enhancing our understanding of extreme events and their future changes. ICoM's research improves understanding of the roles of large-scale meteorological patterns and surface-atmosphere interactions in controlling storms and droughts. Both extratropical cyclones and droughts are strongly influenced by large-scale circulation so understanding potential changes in relevant large-scale meteorological patterns is fundamental to understanding how extratropical storms and droughts respond to warming. ICoM assesses changes in surface-atmosphere interactions, which will inform changes to summer convective storms and hurricanes. ICoM is also using the Energy Exascale Earth System Model to better resolve human-land-river-ocean interactions, in turn leading to a better understanding of changes in extreme precipitation.

Project Activities

- Key precipitation modeling activites include regional convection permitting simluations of Hurricane Ida, Hurricane Irene, and the June 2012 North American derechos (Figure 13).
- Simluations of these extreme storms will be completed at a high spatial and vertical resoultion, and will use the Pseudo Global Warming approach, which imposes a future climate change signal (e.g., 2 degrees of warming) on individual storm events and quantifies changes in storm response (e.g., increase in precipitation).
- ICoM is also investigating changes in storms that occur during different seasons (e.g., summer convective storms versus winter extatropical storms)

Practical Applications

Collectively, ICoM's activities represent a major step toward a long-term vision of delivering a robust, predictive understanding of coastal evolution that accounts for the complex, multiscale interactions among physical, biological, and human systems.

Figure 13. Roadway flooded in Jacksonville, FL, following Hurricane Irma. (Photo by Wade Austin Ellis, Unsplash.)

Supporting Regional Resilience

In Progress

- ICoM provides an improved understanding of how storm events affecting the mid-Atlantic region will evolve in a warming climate. If this information is made accessible, stormwater and wastewater utilities can use this information to inform long-range planning and design. Quantifying how past significant events (e.g., Hurricane Irene and Ida) could change under a warming climate provides information utilities can use to assess how their system would perform under increased stresses and inform risk reduction measures.

- Peer-reviewed publications from ICoM's efforts will improve scientific understanding of the large-scale land and atmosphere drivers of extreme events, which could increase buy-in for using best available science in local scale flood studies.

- ICoM's investigation into how different storm types may evolve under a warmer climate, and how interannual and decadal variability in climate patterns (e.g., the El Nino Southern Oscillation) may exacerbate extreme storms could help communities be better prepared for the extreme events of the future. These climate projections could be used to inform decision-making across utilities.

Recommendations

- ICoM could support regional flood resilience by providing consistent climate projections for stakeholders across the mid-Atlantic region. While stakeholders may use climate projections differently (e.g., different climate scenarios and/or time horizons), consistent regional projections would promote greater consistency and improve cross-jurisdictional coordination and decision-making.

- ICoM's modeling framework for investigating extreme events at a fine spatial resolution can support enhanced climate communication efforts such as rapid climate attribution studies – meaning, a quick assessment of how climate change impacted a storm's peak intensity, duration, or total precipitation. Within days of an extreme event, the contribution of human-attributed global warming in increasing the severity of an extreme event can be quantified and messaged to the broader community. This information not only helps demonstrate the need for stakeholders to incorporate future conditions into planning and design of infrastructure, but also provides valuable information for decision-makers.

- For wastewater and stormwater utilities, ICoM has the potential to provide state-of-the-art climate projections and information that could inform planning, design, and implementation and help fill critical data gaps related to future precipitation. However, these utilities are not currently engaged as ICoM stakeholders. Development of an engagement framework to promote regular and consistent dialog between academic researchers and local utilities and other stakeholders would support the translation of this research into actionable science to support more informed decision-making.

Research Case Study

HyperFACETS - A multi-institutional research effort led by University of California Davis and funded by the U.S. Department of Energy

Summary

The production of actionable climate science relies on effective communication of regional climate information and its associated uncertainties across sectors. To be of value beyond academic circles, climate data must be sufficiently credible (i.e., physically grounded), understandable (communicated in the vocabulary of the decision-makers), and actionable for a decision-making context. The Department of Energy Hyperion and FACETS projects combined to advance a two-way dialog between scientists and end users, with a focus on 1) advancing the understanding of processes at the climate-water-energy-land-decision interface, and 2) improve the ability to perform credible climate modeling of particular regions. Specifically, HyperFACETS addresses two key questions: How much can we trust given climate information for actionable science? And how we can ensure its saliency?

HyperFACETS research is national in scale and extends beyond understanding future extreme precipitation. This case study focuses on the aspects of HyperFACETS that are most relevant for characterizing how extreme events may change under a warming climate.

Partners

This project is led out of University of California Davis, with representation from Stony Brook University, Cornell University, Iowa State University, Pacific Northwest National Laboratory, University of California Los Angeles, Pennsylvania State University, Climate Readiness Institute, Utah State University, Lawrence Berkeley National Laboratory, and the National Center for Atmospheric Research.

The Challenge

Creating actionable climate science in the face of uncertainty relies on effective communication across multiple sectors, and between scientists and practitioners. HyperFACETS seeks to extend the value of climate research beyond the academic realm and translate comprehensive assessments of climate models for decision-makers. As a core component of its approach, HyperFACETS creates metrics to evaluate model performance and climate projection credibility through a process that integrates scientists and end-users throughout.

The Approach

The Department of Energy's Office of Science sponsors HyperFACETS through the Regional and Global Model Analysis and MultiSector Dynamics program areas. Climate simulations are conducted across various regional scales following different land use, irrigation, and energy scenarios.
One approach embraced by the HyperFACETS team that is of particular interest to stormwater / wastewater utilities is the storyline concept. Extreme events (e.g., droughts, floods, and extreme winds) that have historically affected stakeholders are selected. These events are hindcast to recreate the past event and modeled in the future to assess the response of the storm event to a warming climate. HyperFACETS focuses on a wide range of events that impact multiple sectors. To date, much of the work has focused on informing the renewable energy sector (e.g., how changes in precipitation and wind patterns may impact hydropower or wind energy generation, respectively). However, historical extreme events that impacted stormwater/wastewater utilities could be selected, and the findings, when appropriately translated, could inform actionable decision-making (see San Francisco's Extreme Precipitation Box as an example).

Project Activities

The project has been categorized into five interwoven tasks:

1. Engaging climate scientists and stakeholders - continuous outreach and engagement to ensure a focus on stakeholder needs
2. Developing storylines – evaluating historical extreme events that resulted in (or would result in) significant impacts in both the historical and future climate, to better inform policy and decision-making
3. Evaluation metrics – use of existing metrics and design of new metrics to help understand model performance and support credibility of climate projections. Identifying biases and errors that result in uncertainty
4. Credibility analysis – quantify validity of climate models and projections for decision-making
5. Deeper understanding - of multi-sector interactions, the interplay between global and regional climate forcings, and implications for the energy sector

The HyperFACETS storylines are founded on historically impactful events that occurred across different regions in the US and were driven by different processes (e.g., storm types). These extreme event examples are representative of extreme events that impact the stormwater/wastewater sector. From the full storylines catalog, storms relevant to stormwater and wastewater utilities include:

- Sequential atmospheric rivers that occurred in California over 43 days resulting in compound flooding and damage
- Hurricane Irma, which brought significant damage to the southeastern coast
- Repeated mesoscale convective systems (thunderstorms) over the southern great plains which brought the worst flooding on record in Texas, and
- Rain on snow flash flooding due to extratropical cyclones landfalling on the eastern coast.

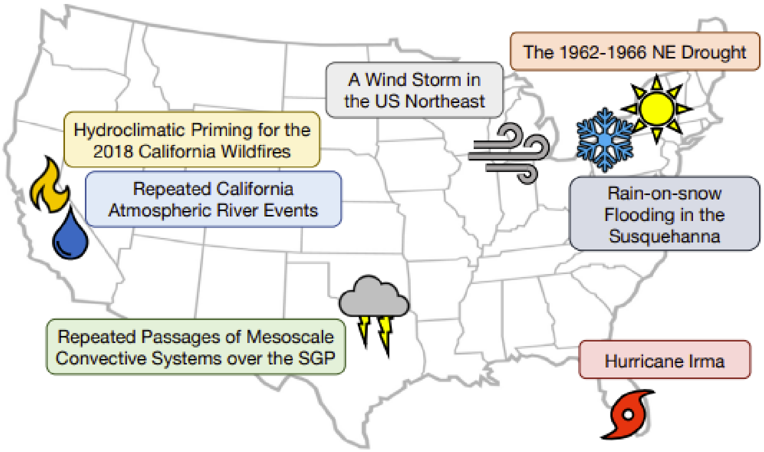


Figure 14. Infographic developed by the HyperFACETS team to depict the different storylines catalogues. (Image from: https://climatemodeling.science.energy.gov/system/files/publications/attachments/HyperFACETS.pdf, accessed December 29, 2022.)

Practical Applications

HyperFACETS research activities include an impressive catalog of historical extreme events that have impacted communities across the entire contiguous US. The research goals of producing actionable climate science that provide value beyond academic circles are critical for developing policies, products, and tools that can inform decision-making and contribute to wise infrastructure investments and resilience planning.

Supporting Regional Resilience

In Progress

- HyperFACETs seeks to better understand the factors that contributed to the occurrence of significant historical extreme events and how they could worsen with a changing climate using a storyline approach.

- Peer-reviewed publications from HyperFACETS will improve scientific understanding of a wide range of extreme events and compound events, which could increase buy-in for using best available science in local scale flood studies.

- For the South Florida region, Hyperion/ HyperFACETs advanced climate modelling by evaluating regional climate datasets for decision-relevant metrics. An outcome of evaluating the best performing climate models from the North American CORDEX ensemble and the Variable-Resolution Community Earth Systems Model (CESM) was future projections of precipitation Intensity-Duration-Frequency curves for the Susquehanna watershed and Florida peninsula. This process can be replicated across additional geographies to provide consistent precipitation projections for a wide spectrum of stakeholders to support regional resilience activities. However, to ensure continued success of this effort for utilities, additional engagement with stakeholders will be required to increase interest and support.

Recommendations

- An expansion of the stakeholders to include stormwater and wastewater utilities, and the translation of the model results to actionable science for decision-making, could provide substantial resilience benefits across the nation.

- The outcomes of the storyline assessments could allow a broader range of additional stakeholder interests to be met, including extreme precipitation projections for use in developing design storm curves.

- An assessment of historical storms that caused significant impacts to stormwater and wastewater utilities, in particular compound events, could help expand the range of extreme events of interest under HyperFACETS.

- For wastewater and stormwater utilities, HyperFACETS has the potential to provide state-of-the-art climate projections and information that could inform planning, design, and implementation and help fill critical data gaps related to future precipitation across the nation. However, stormwater and wastewater utilities are not currently engaged as HyperFACETS stakeholders. Development of an engagement framework to promote regular and consistent dialog between academic researchers and local utilities and other stakeholders would support the translation of this research into actionable science to support more informed decision-making.

Observations and Recommendations

As demonstrated through the literature review, findings from the national-scale survey, and the case study deep dives, stormwater and wastewater utilities' engineers and decision-makers recognize that climate change has impacts on water management today. If future utility upgrades and maintenance neglect to consider forward-looking climate projections that point to even more dramatic precipitation shifts in the future, utilities can expect further impacts to their assets and operations. However, engineering tools, standards, and guidance documents typically do not incorporate climate non-stationarity and the projected increased occurrence of extreme storm events. This is a major gap for stormwater and wastewater utilities.

It is important to remember that stormwater and wastewater systems are usually not designed to handle the most extreme precipitation events today. Equally, future upgrades will also not be designed to protect systems and communities from the most extreme events in the future. While designing for the unprecedented storm of 2100 may not be feasible, preparing for today's unprecedented storm (which is tomorrow's more common occurrence) is necessary. Moreover, understanding how extreme storms can intensify in a warmer climate will help utilities prepare and develop contingency plans for when more extreme storms do occur. Providing a robust and consistent suite of products that help these utilities plan for future storms is therefore paramount.

To close, this report identifies five key observations and recommendations.

1. Real-time observations and monitoring of current storms and weather patterns play an important role in our ability to understand natural variability and predict future, climate-impacted weather patterns.

What Is Used Today:

Observations provide vital information and a foundation for understanding future climate impacts, including changing precipitation patterns. Consistent monitoring of environmental conditions helps identify existing patterns and provides a baseline to which future climate model output can be compared. However, relying solely on historical storms and observations underestimates risk from future storms. For example, NOAA Atlas 14 often underpredicts current storms, is outdated in many regions, and assumes a stationary climate system. Moreover, some regions, such as the Pacific Northwest, still rely on NOAA precipitation estimates from the 1970s, hampering their ability to adequately prepare for today's storms.

Header photograph courtesy of Philadelphia Water Department

What is Needed for Tomorrow:

Funding from the 2022 Bipartisan Infrastructure Investment and Jobs Act (BIIJA) requires NOAA to update precipitation data nationally through Atlas 15. In addition, the recently signed PRECIP Act (S.3053/H.R.1347) requires that "NOAA shall, no less than every 10 years, update probable maximum precipitation estimates for the United States." To account for changing storms, Atlas 15, and any work carried out under the PRECIP Act, must include non-stationary climate change projections. If this is not feasible, alternate actionable datasets at a national scale could be created that complement Atlas 15 and incorporate forward-looking precipitation projections. Concurrently, continued investment in weather monitoring and observation systems will bolster the development of a consistent baseline to better understand today's storms, validate predictions and inform future projections.

2. Global Climate Models (GCMs) are integral to future planning. Continued refinement of outputs to represent localized storms and conditions and/or development of alternate methods to characterize changing precipitation extremes will help lead to more climate resilient stormwater and wastewater systems.

What Is Used Today:

Challenges remain in scaling future IDF curves for storms with shorter durations. This is due to limited (albeit increasing) availability of fine scale climate models with long-term, sub-daily output, as is required to resolve complex storm dynamics including convective precipitation and other key drivers of local precipitation (e.g., topography, land cover, and land-sea interactions). Efforts are underway across the nation to develop actionable precipitation projections, but these efforts use different approaches, assumptions and results, which can lead to confusion for utilities trying to identify the "best" or "right" information to use. Additionally, some projects to develop actionable precipitation projections are specific to a particular utility or locality, and approaches utilized may differ among utilities even within a single region.

What is Needed for Tomorrow:

Climate modeling that develops more targeted regional modeling, with sub-hourly projections, allows utilities to better frame the certainty, or uncertainty, associated with how a project will meet performance standards in the future. This refined modeling should be made available across the nation so all utilities have the same level of access to the same actionable science. In the absence of high resolution GCM output, climate scientists could make recommendations to practitioners to estimate potential changes in future extreme precipitation, relying on the latest scientific literature and application of physical principles, like the Clausius-Clapeyron relationship. In coastal areas, there is also a need to assess compounding impacts from pluvial, fluvial, groundwater, and coastal flooding. Adequate consideration of multiple hazards may require additional modeling and resources that are informed by the evolving GCM outputs.

Figure 15. Flooded roadway in Philadelphia. (Photo courtesy of Philadelphia Water Department.)

3. Top-down policy drivers and standardized practices are needed.

What Is Used Today:

There is a lack of standardized practices and guidance at the federal, state, and local levels. There is often no requirement to assess or include future conditions in water utility infrastructure planning, operations and maintenance, upgrades, or new construction. From experience with current storms and recognition that these storms will only get worse, many utilities are proactively working to include future conditions in their infrastructure designs. For those ready to act, there is a lack of guidance on how to incorporate the latest science or new information, or practical guidance on how to deal with uncertainty and move past waiting for the “best” or “right” information. As an example, adaptive management or planning is a process by which utilities can 1) understand a range of future projections and impacts, 2) identify triggers for when to respond to impacts and identify appropriate strategies, and 3) use observations to inform when triggers are met and therefore when to enact a strategy. While utilities understand this process conceptually, there is little guidance for how to do this in practice.

What is Needed for Tomorrow:

There is a need for a consistent suite of tools and guidance that provide transferable methodologies and leading practices across the nation’s stormwater/wastewater utilities. This could entail development of a roadmap that outlines a clear path from the start of an analysis, to planning for, and subsequently to implementation of an infrastructure project or long-term plan. A roadmap could also provide recommended pathways to help all utilities access and use the proposed actionable science described above (#2). This roadmap or guidance should also be combined with technical assistance directed at less well-resourced utilities to ensure equitable uptake. The roadmap should not provide prescriptive guidance that recommends a certain level of service or design storm, but rather be utility-led and provide for flexibility when applying information and tools to specific local conditions and various project contexts.

Figure 16. Coastal street flooding, Florida. (Photo courtesy of AlteredSnaps, Pexels.)

4. Funding generally comes from a small pool of federal funders and is not enough to drive sustained action.

What Is Used Today:

Utilities fund their climate change work and general system maintenance and improvements through various financial mechanisms, including ratepayer funds, municipal bonds and grants. Large-scale infrastructure upgrades require significant and sustained investment, particularly as climate impacts continue to exacerbate current conditions and increases risks. Moreover, as climate impacts increase, there will be more pull for resources from the federal government across all climate impacts beyond just those related to precipitation (e.g., extreme heat, sea level rise, and fire).

Most grants identified through the literature review were from federal sources. The National Association of Clean Water Agencies (NACWA) cites that, according to the Congressional Budget Office, funding from the federal government has declined over recent decades to less than 5 percent of total investment in water and wastewater infrastructure across the United States. This decline in federal funding has shifted the burden of infrastructure maintenance, renewal, and replacement to utilities and their customers/communities. While recent legislation, like the Bipartisan Infrastructure Law and the Inflation Reduction Act, will provide for a significant influx of federal funds, the magnitude of infrastructure investment needs remains daunting. The US EPA estimates that, over a 20-year period, $744 billion in infrastructure-related capital costs are needed to maintain wastewater and drinking water systems (CRS, 2022). To maintain affordable services, utilities cannot raise their rates to the extent needed. While grants have played a critical role in infrastructure funding, they pose other capacity-related challenges. Staff resources (and expertise) are needed to track different grant opportunities, pursue relevant opportunities, and then manage any awarded grants and their sometimes onerous and time/resource-consuming reporting requirements.

What is Needed for Tomorrow:

Utilities, in collaboration with relevant stakeholders and local, state and federal partners, will need to identify sustained sources of funding and revenue generation that allow the flexibility needed to respond to emergencies and proactively prepare for future climate conditions. Limitations in regard to raising customer rates, devoting resources to grant applications and management, and the scale of continued investment needs must be considered. Utilities would benefit from more streamlined grant processes, expanded technical assistance and large-scale influxes of federal funds, such as the forthcoming monies in the Bipartisan Infrastructure Law and the Inflation Reduction Act. WUCA could provide a unified voice to advocate that funding agencies scale-back on grant administrative requirements and/or provide the necessary technical assistance for less resourced utilities to develop competitive grant applications. Similarly, given the scale of the climate resilience challenge across the entire nation, and not for just individual wastewater and stormwater utilities, WUCA could advocate for earmarked and/or directed agency funding to help stormwater and wastewater utilities prepare for climate change, similar to the funding that has been made available for energy infrastructure.

Figure 17. Overflowing stormwater, Seattle. (Photo Courtesy of Seattle Public Utilities.)

Figure 18. Flooding in Pioneer Square, Seattle, WA. (Photo courtesy of Seattle Public Utilities.)

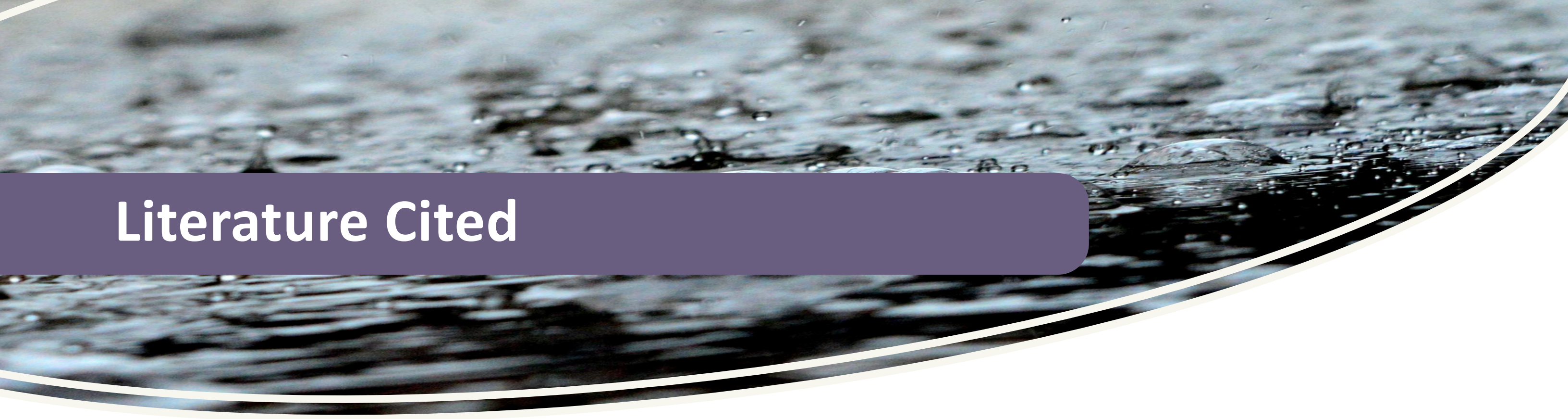
5. Important and sophisticated research is underway, and many practitioners are acting, but there still is a large disconnect between research studies and practical application.

What Is Used Today:

Climate modeling is a key component for informing future water management, but many different actors hold different pieces of information and there is limited opportunity or guidance for how best to connect the different actors and their respective pieces of the puzzle. Partnerships among academic/research organizations, water utility engineers and managers, and consultants and engagement specialists, can provide a bridge between the latest scientific advances and forward-looking utility management. SFPUC's partnership with LBNL, Pathways, and other City of San Francisco departments (see Box) is an example of such a partnership. This partnership helped frame the research to the specific needs of SFPUC and San Francisco, overcame some of the technical capacity limitations within the utility, and provided access to supercomputers for sophisticated regional scale modeling and the translation of the modeling to actionable science. This partnership is a successful model that can be replicated. As different problems are solved at individual utilities, peer-to-peer learning can then help other utilities as they tackle similar or new problems. These partnerships can also provide credibility and help advance newer climate adaptation strategies to more risk-averse partners.

What is Needed for Tomorrow:

Collaboration between research institutions, federal agencies, and practitioners/utility staff is needed to support guidance and to develop a consistent roadmap for moving forward. Stakeholder engagement is needed across regional research studies to produce actionable outputs. This could be incentivized if cross-sector coordination were included as a grant activity and funding requirement. Developing actionable and accessible products requires two-way communication. Industry experts must clearly communicate their needs to the climate scientists. In parallel, climate scientists interested in developing useful, usable, and accessible data products should seek out industry experts to inform product development and consider additional simulations or re-frame research efforts to better support industry end users. The newly signed PRECIP Act provides a timely opportunity to incorporate perspectives from stormwater/wastewater utility experts and practitioners as part of the mandated National Academies study and recommendations to NOAA. WUCA represents an excellent platform for enhancing communication between climate scientists and practitioners, but this collaboration will require active effort and continued communication.



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Appendix A

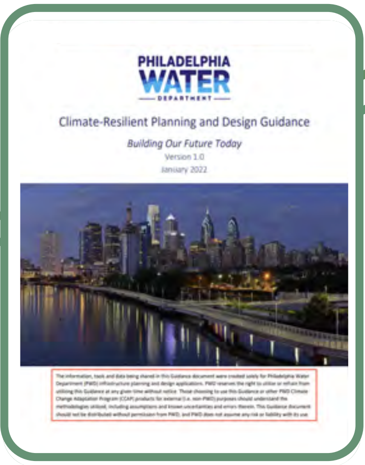
Appendix Table of Contents

Header phototograph courtesy of Seattle Public Utilities

Scaling and Application of Climate Projections to Stormwater and Wastewater Resilience Planning

Case Study: Philadelphia Water Department

Transforming Global Climate Model Precipitation Output for Use in Infrastructure Planning and Design Applications



PHILADELPHIA WATER DEPARTMENT

Climate-Resilient Planning and Design Guidance

Building Our Future Today

Version 1.0

January 2022

The information, tools and data being shared in this Guidance document were created solely for Philadelphia Water Department (PWD) infrastructure planning and design applications. PWD reserves the right to utilize or refrain from utilizing this Guidance at any given time without notice. Those choosing to use this Guidance or other PWD Climate Change Adaptation Program (CCAP) products for external (i.e. non-PWD) purposes should understand the methodologies utilized, including assumptions and known uncertainties and errors therein. This Guidance document should not be distributed without permission from PWD, and PWD does not assume any risk or liability with its use.

Summary

Philadelphia Water Department (PWD) led an initiative to develop guidance based on in-depth analysis of climate projections. The Guidance is informing a department-wide revamp of standards and criteria for resilience planning.

The Backstory

The Philadelphia Water Department formed a Climate Change Adaptation Program (CCAP) in 2014 to study and address PWD's vulnerabilities and risks to climate change impacts. In preparation, a department-wide survey gathered input from staff on perceived PWD vulnerabilities related to climate change to help identify the most immediate, or primary, planning needs for adaptation. Sea level rise and increasing precipitation were identified as the climate risks with the biggest potential consequences to employee and customer health and safety and PWD core services, including the provision of clean and safe drinking water. To address the primary planning needs, CCAP developed actionable climate change science and information.

The Challenge

While statistically downscaled global climate model (GCM) precipitation output is available for Philadelphia, the temporal resolution is too low for direct use in model-based urban stormwater applications and GCM output for Philadelphia does not accurately represent local storm intensities and durations. In addition, there were challenges related to climate risk planning at PWD given the evolving science and lack of a regulatory driver.

Project Timeline 2018-2021
Project Area/ Geographic Scale City of Philadelphia
Study Focus Precipitation Projections, Climate Impacts
Lead Agency Philadelphia Water Department (PWD)
Target Audience PWD staff, various City departments
Type of Data Used Observed precipitation data, statistically downscaled Global Climate Model (GCM) output.
Types of Precipitation Inputs Used Timeseries and design storms (IDF curves)

The Approach

To address the challenges, PWD completed a study (Maimone et al. 2019) that used an innovative approach to transform GCM output into actionable science that can directly inform planning, design, and engineering applications, including hydrologic and hydraulic (H&H) modeling and intensity-duration-frequency (IDF) curve development. The approach uses GCM output for current (1995–2015) and future (2080–2100) conditions under the Representative Concentration Pathway (RCP) 8.5 greenhouse gas emission trajectory to develop delta change factors based on season and storm size. These factors were then used to create a plausible future hourly time series. A stochastic generator was used to explore potential variability in projected precipitation patterns to better understand the range of uncertainty. The approach used is practical and transferable, addressing the need for locally relevant and actionable climate change information in the field of water resource management.

The Barriers

The climate projections and planning recommendations are captured in the first iteration of the PWD Climate-Resilient Planning and Design Guidance (January 2022), the culmination of the effort. The Guidance provides staff across multiple departments with the information and tools necessary to make decisions in the face of uncertainty and to include forward-looking climate risk information in all planning and design efforts, including those related to structural and non-structural systems. Official PWD policy requiring use of the Guidance in infrastructure planning and design efforts, to the extent feasible, was adopted in January 2022.

Practical Applications

Several projects have been informed by the Guidance since its release, including PWD stormwater and wastewater drainage system projects, a Water Pollution Control Plant (WPCP) effluent pump station design, and planning associated with raw water pump stations at risk of riverine flooding during extreme rainfall events.

Flooded roadway in Philadelphia. (Photo courtesy of Philadelphia Water Department.)

Project Data and Methods

Data inputs and outputs	Observed precipitation data and statistically downscaled Global Climate Model (GCM) data. Outputs include future high resolution timeseries and future IDF curves (extreme precipitation).
Data source	NOAA PHL (Philadelphia Airport) rain gauge, PWD rain gauge network (citywide), CMIP5 statistically downscaled output (LOCA) (https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html).
Time Horizons / Climate Scenarios Used	Since most of PWD’s assets have a very long service life the department is currently planning to at least mid-century and usually end-of-century (2100). PWD is considering changes in the intensity and frequency of future storms, as well as the increasing occurrence of cloudburst events (i.e., extreme precipitation). The RCP8.5 climate projections are generally used because PWD is a critical service provider with a low risk tolerance.
Updates to model runs with the latest IPCC GCM data?	Current Clean Water Act and Safe Drinking Water Act regulations do not require PWD to account for climate change; therefore, some modeling applications/simulations have yet to be updated with the latest climate projections. Despite the lack of a regulatory driver, this effort produced future condition precipitation timeseries for use in PWD H&H models, and department-wide policy requires the use of future condition precipitation inputs in project and program planning, to the extent feasible and per information contained in the Guidance. Some capital projects on both the water and wastewater side, as well as some planning efforts related to the drainage system, have already incorporated future condition precipitation and/or sea level rise projections based on the new Guidance.
Use of Precipitation Projections	Hourly or sub-hourly precipitation timeseries are required for most urban stormwater modeling applications; design storms and IDF curves are required for planning and design of sewers.
Objective for Using Future Precipitation Projections	Incorporate future condition information into planning and design of infrastructure systems/assets, including H&H modeling of combined sewer system and alternatives analyses for flood risk management projects.
Application	For various capital projects, the planning and design process is accounting for climate change projections, per the Guidance document.
Events Driving Action	Hurricane Ida impacted the PWD service area during the final stages of rolling out the Guidance, serving as an “eye-opener” as to what can happen as extreme events become more extreme under a warming climate. This attested to the immediate need for this Guidance and helped support acceptance.

Lessons Learned

1. Do not let perfect become the enemy of progress and focus on actionable information

In developing the Guidance document, PWD accepted that there will always be uncertainty associated with climate projections and developing a singular and 'certain' projection is not practical or feasible in a field that is based on continually evolving science. The important aspect is to gain agreement that there is enough certainty in the projections to use them for making decisions and recommendations. To better understand what uncertainties do exist and how science can be made actionable, prioritize engaging with federal agencies, like NOAA and NASA, as well as climate scientists from the academic community and National Labs.

2. Involve staff early and continuously on climate change related discussions; identify and rely on climate champions

PWD recognized the importance of involving staff from the beginning. This program began in 2014 by engaging staff (with a survey reaching multiple units and programs) to understand their impression of PWD's primary climate change vulnerabilities. The feedback gathered helped to identify the climate-related consequences associated with various climate impacts, including increasing precipitation. When developing the Climate-Resilient Planning & Design Guidance, staff provided input and review of the content at multiple points in the development process (for example, CCAP asked the questions: What tools would be most helpful? What output format would support your work? What hesitations do you have in terms of using this information and how can we help address those?). CCAP also worked to identify and develop relationships with 'climate champions' in various programs throughout the Department.

3. Stress that climate change is happening here and now

When it came to generating support and buy-in, PWD learned the importance of highlighting that climate change is happening here and now by drawing focus to recent extreme events. For example, in engaging with Executive Staff on the Guidance and the need for a department-wide policy, CCAP highlighted the devastating local impacts of Hurricanes Isaias and Ida, and the fact that climate change will make these extreme events more likely. Based on these recent events, it is already evident that PWD needs to account for increasing storm intensities and climate projections in infrastructure planning and design.

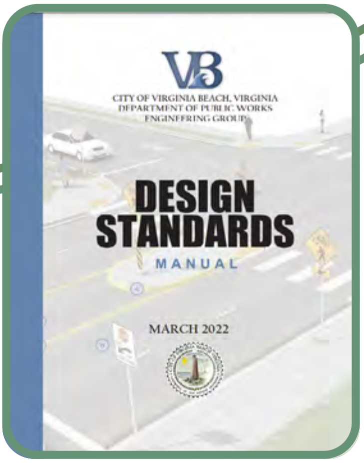
4. Top-Down directives are needed to empower staff

PWD used a 'bottom-up' approach to develop the Guidance document and gain staff buy-in, but ultimately top-down directives (e.g., a new policy) were needed to empower staff to use climate projections in their work and support the consistent application of the information in existing and long-standing programs/processes.

Scaling and Application of Climate Projections to Stormwater and Wastewater Resilience Planning

City of Virginia Beach, Department of Public Works

Developing Future Precipitation Projections and Design Standards



VB
CITY OF VIRGINIA BEACH, VIRGINIA
DEPARTMENT OF PUBLIC WORKS
ENGINEERING GROUP
DESIGN STANDARDS
MANUAL
MARCH 2022

Summary

The City of Virginia Beach commissioned a study to assess changes in historical and future extreme precipitation in response to heavy flooding events. The study, which received a third-party review, resulted in updates to the Department of Public Works Design Standards Manual (2020), including new requirements and design parameters for stormwater management. The effort also included an assessment of sea level rise and the potential for combined flooding impacts from extreme precipitation and storm surge events.

The Backstory

In 2016, Virginia Beach experienced a series of three large storm systems (tropical storms and hurricanes) back-to-back that brought 33 inches of rain in a 6-week period. The heavy flooding resulted in increased interest in considering the influence of climate change on extreme precipitation.

The Challenge

The best available precipitation information in 2016 was NOAA Atlas 14, which is baselined to the year 2000 and does not consider future climate change. A review of two long-record rain gauges showed that the NOAA Atlas 14 10-year rainfall event is about 7 to 10% below local observational data, and it was not representative of the extreme precipitation during the 2016 hurricane season.

Project Timeline
2014-2020

Project Area/ Geographic Scale
City of Virginia Beach

Study Focus
Extreme Participation,
Sea Level Rise, combined flooding (rainfall/surge correlation)

Lead Agency
Department of Public Works

Target Audience
City of Virginia Beach, Developers, Residents

Type of Data Used
NA-CRODEX regional climate models (CMIP5)

Types of Precipitation Inputs Used
Historical rain gauge data

The Approach

In 2015 the City began an initiative called Sea Level Wise to evaluate sea level rise and flood risks. In response to the 2016 flood events, this was extended to include analyses of historical and future extreme precipitation projections. The observational trend showed an increase of 3 to 7% per decade for the 10-year event, and future projections suggested potential increases of 7% for RCP4.5 and 24-27% for RCP8.5 by 2060 (relative to the year 2000). Using a combination of the historical trends and future projections, the city recommended the use of a 20% increase in extreme precipitation by the year 2060, assuming a 40-year lifecycle for infrastructure projects.

The analysis was reviewed and verified externally by the Virginia Department of Transportation and the Transportation Research Council. The dual verification provided confidence in the analysis, and Public Works submitted their recommendations to the City Council for approval. The City Council unanimously approved the use of the future precipitation estimates in June 2020, resulting in an update to the Design Standards Manual which applies to both public and private projects.

The Outcome

The Design Standards Manual updates included design standard changes to address future precipitation estimates, recurrent flooding, and sea level rise risks. The updates also required using this information in the City's Storm Water Management Model (SWMM). The city is continuously updating their SWMM master model to better represent the stormwater system, and these updates, combined with the future precipitation updates, have allowed the city to be proactive in their efforts to reduce flood risks.

Practical Applications

Projects are designed using the revised design guidelines. The Design Storms and Hydrologic Methods requires that designers must increase the NOAA Atlas 14 design storm rainfall depths by 20% and must use dynamic modeling (SWMM) to analyze the pre- and post-development conditions, except for areas less than 20,000 sq. feet.

The City of Virginia Beach uses the updated design storms in the Master Drainage Model (MDM) which includes the Primary Stormwater Management System (PSMS) for the majority of the City. This model allows the city to identify the areas of greatest risk and prioritize projects to reduce the flood risks.

Street flooding in Virginia Beach. (Photo Courtesy from Virginia Beach Fire Department.)

Project Data and Methods

Time Horizons / Climate Scenarios Used	All rain gauges within a 60-mile radius were used. Ensemble approach used regional climate models within the NA-CRODEX archive, using medium emissions (RCP4.5) and high emissions (RCP8.5) scenarios. Applied bias correction to allow for direct comparison between projected precipitation-frequency curves and NOAA Atlas 14 guidance for easy interpretation. All simulations were conducted using variable resolution (11- and 44-km). The findings from the historical trends and both future condition scenarios were blended to account for uncertainty.
Updates to model runs with the latest IPCC GCM data?	Consistently updating SWMM models as data becomes available (typically every 3 months).
Objective for Using Future Precipitation Projections	Reduce stormwater flood risks, including flooding exacerbated by sea level rise and rising groundwater. Accurately describe and prepare for increasing extreme precipitation events.
Application	Department of Public Works Design Standards Manual

Lessons Learned

1. Confirm and identify the question at hand

It is important to confirm the questions to be answered and the desired outcomes (e.g., updates to design standards) from the outset to help streamline the process and gain agreement across multiple parties.

2. Use best available science and data

The city relied on multiple rain gauges, used the best available data, and clearly documented their analysis approach and results. This allowed two independent third parties (Virginia Department of Transportation and the Transportation Research Council) to review and validate the methods and findings. This provides confidence in the process.

3. Do not wait, get started

These studies and the corresponding updates to existing design standards can require multiple years for planning, analysis, and implementation. The most difficult step is getting started. Waiting for the “most up-to-date” data impedes advancements.

4. Rely on regional efforts

The City of Virginia Beach benefited from a series of “green light” situations that eased the entire process (from analysis, to adoption, to implementation). There was sufficient budget, political support, and staff capacity to move this effort forward. However, the city recognizes that this is not always the case. Under alternative circumstances, the city could have waited for a regional effort to be completed to inform similar updates.

Scaling and Application of Climate Projections to Stormwater and Wastewater Resilience Planning

Seattle Public Utilities and King County

Ship Canal Water Quality Project – Combined Sewer Overflow Program – Preparing for Extreme Rainfall with Climate Ready Design

Ship Canal
WATER QUALITY PROJECT

Seattle Public Utilities

King County

Project Overview

Investing in the Health of the Sound and the Future of Our Region

How we're working with the community

Keeping our website updated

Available to listen and connect you with the right person

Staffing drop-in and community events

Working with community groups

Sending biweekly program emails

Contact

Summary

Seattle Public Utilities' (SPU's) Ship Canal Water Quality Project used both observations of increased precipitation and overflows with modeled future extreme precipitation projections to inform the design of a 2.7-mile-long storage tunnel to manage combined sewage and stormwater overflows into the future.

The Backstory

During heavy rains, Seattle's combined stormwater/wastewater system experiences overflows that can send polluted stormwater and wastewater into the Lake Washington Ship Canal, Salmon Bay and Lake Union. Driven by a consent decree obligation to reduce these overflows, SPU and King County Wastewater Treatment Division (King County) initiated the Ship Canal Water Quality Project in 2013. The project, SPU's largest ever infrastructure investment, includes building an underground storage tunnel that will significantly reduce the amount of polluted stormwater and wastewater that flows into the Ship Canal waterway. The project will be operational in 2025 and is expected to prevent an average of 75 million gallons of combined stormwater and wastewater from entering Seattle's waterways each year.

The Challenge

The Ship Canal Water Quality Project's design began in 2013 with an expected completion date in 2025. Taking climate change into consideration, initial designs included a 6% scaling factor to account for potential future precipitation increases. This scaling factor was selected based on early model projections that suggested a 0 - 15% increase in extreme precipitation by the end of century. However, the combination of heavy rains in 2015 and 2016 and improvements in climate modeling, specifically related to extreme precipitation projections, suggested that the 6% scaling factor would not be adequate to prevent future overflows.

Project Timeline
Project initiated in 2013. Expected completion in 2025.

Project Area/ Geographic Scale
Ship Canal, between Puget Sound and Lake Union, in the City of Seattle and King County, WA

Study Focus
Extreme Participation, Stormwater Flooding, Preventing Sewer Overflows, Combined System Storage

Lead Agency
Seattle Public Utilities and King County Wastewater Treatment Division

Target Audience
PWD staff, various City departments

Type of Data Used
Observed precipitation records, statistically and dynamically downscaled global climate models

Types of Precipitation Inputs Used
Spatially varying timeseries

The Approach

SPU and King County considered several options before deciding on the underground storage tunnel. Alternative options included green infrastructure and local detention facilities. Overall costs were similar, but the tunnel resulted in fewer impacts to nearby communities and greater operational flexibility.

The initial design phase considered a 14-foot (ft) diameter storage tunnel. To support the project, SPU updated its rainfall statistics using historical data and future precipitation projections. The preliminary results revealed that observed precipitation trends showed that current precipitation values had already increased more than the 6% assumed to account for future increases. These results were consistent with similar analyses completed by King County, as well as observations from 2015 and 2016.

The Outcome

The Ship Canal Water Quality Project storage tunnel size was increased in diameter from its original design of 14 ft to 18 ft 10 inches (in), to capture the expected increase in stormwater volume. The upsizing of the tunnel from a unique diameter (14 ft) to an industry standard size (a size often used for transportation tunnels) also minimized additional capital cost. The larger diameter design increased the tunnel storage volume from ~15-million gallons to about 30-million gallons with only $30 million in additional costs.

Practical Applications

The engineers' in-depth knowledge of existing performance issues paired with improved existing and future condition precipitation analyses led to concerns about the initial proposed tunnel size. SPU and King County made the decision to upsize the tunnel. With leadership on board, and community support for the larger project, the project moved forward with the larger storage volume design.

MudHoney, the 18 foot diameter Tunnel Boring Machine, and crew will build the conveyance tunnel for the Ship Canal Project. (Image courtesy of Seatte Public Utilities.)

Project Data and Methods

Data inputs and outputs	Observed precipitation. SPU uses statistically downscaled GCMs and King County uses dynamically downscaled GCMs.
Data source	SPU has used two approaches for estimating future precipitation. The original approach used at the project's inception (2010-2014), was based on the correlation that one degree (Celsius) increase of North Pacific temperature would result in approximately 6% more precipitation (the Clausius-Clapeyron relationship). This was the approach SPU had previously used for SPU's combined sewer overflows (CSO) long-term control planning. The revised approach used the best available IPCC AR5 global climate model output along with historical analysis that considered recent changes to observed precipitation trends.
Time Horizons / Climate Scenarios Used	Preliminary analysis relied on historical rainfall measurements. The analysis indicated that engineers should use a scaling factor of 3 – 4% over baseline for precipitation by 2035 and a 12 – 14% increase over baseline by 2100. An average scaling factor of 6% was initially used to inform the tunnel design. Following the heavier than average rainfall in 2015 and increased overflows in 2016, both SPU and King County developed new climate models and updated future projections.
Updates to model runs with the latest IPCC GCM data?	Building off their latest model initially developed in 2017, SPU is committed to incorporating new precipitation information as updated observations and future projections become available.
Use of Precipitation Projections	Hourly or sub-hourly precipitation timeseries are required for most modeling applications; design storms and IDF curves are required for planning and design.
Objective for Using Future Precipitation Projections	Reduce combined stormwater overflows by accounting for future extreme precipitation increases. Account for extreme precipitation in the design of the underground storage tunnel to prevent future combined stormwater and wastewater overflows.
Application	SPU and King County used new information to update the design of the underground storage tunnel, with the goal of reducing combined sewer overflows in the future, under increased precipitation extremes.
Barriers and Challenges	Lack of climate science expertise within the agency provides one barrier. Updating infrastructure to prepare for changing climate conditions requires significant funding, usually above base funding allocations. Ensuring equitable climate preparations across all communities is another challenge. King County is prioritizing the additional funding needed for climate resilience within vulnerable communities that have environmental justice burdens. As this project was for a more affluent community, the County did not fund the climate resilience upgrade.
Events Driving Action	Hurricane Ida impacted the PWD service area during the final stages of rolling out the Guidance, serving as an "eye-opener" as to what can happen as extreme events become more extreme under a warming climate. This attested to the immediate need for this Guidance and helped support acceptance.

Lessons Learned

1. Communicate uncertainty as part of the performance standard to support decision-making.
Rather than rely on a single, set number that may prove incorrect in subsequent years, SPU and King County engineers recognized the value of explaining the range of uncertainty to decision-makers relative to meeting performance standards. If a solution provides a 70% certainty of meeting a performance standard in the future, and decision-makers request an increase to 80 to 90% certainty, overall agency support and buy-in increases. Communicating uncertainties clearly and in a relevant metric can be a powerful tool and can help manage expectations about future changes (e.g., updated science) that could occur later in the design process.

2. Intentionally look at the long-term resiliency of a project.
With hindsight, project team members indicated more robust analysis of observed and future precipitation should have occurred at the beginning of the project. They indicated that the initial approach of applying the average scaling factor of 6% across the lifetime of the project was too simplified and didn't fully account for changes in future condition extreme events. In retrospect, project leads indicated that had they looked at more extreme future scenarios, they may have recognized the increased resilience a larger more-standard diameter tunnel could provide, without a proportionate increase in cost.

3. Climate change is one of many factors influencing project design.
For SPU, the primary driver was regulatory compliance and understanding the potential risks that could occur in the future based on sizing facilities for historical rainfall instead of future projections. As updated science became available, the risk of potential future non-compliance increased, resulting in a design change.

4. Lack of clear climate policies can still lead to resilient decision-making.
Although policies existed for sea level rise, there were no clear policies on how to consider precipitation-related climate impacts during the design phase for this project. However, the robust analysis of future precipitation developed for this project is informing other projects. SPU is one of the most proactive City departments in integrating climate science into capital projects and operations. SPU's approaches are likely to become a model for other departments as adaptation planning and investment becomes more standard.

Scaling and Application of Climate Projections to Stormwater and Wastewater Resilience Planning

Chesapeake Stormwater Network

Developing a Regional Resilience Framework

Summary

A regional effort to standardize stormwater practices within the Chesapeake Bay Watershed through the Chesapeake Stormwater Network (CSN) and affiliated partners. Seeking to establish best management practices (BMP) for future resilient designs that consider future climate change.

The Backstory

The Chesapeake Bay Watershed (Bay) consists of seven states across the Mid-Atlantic. The region primarily relies on NOAA's Atlas 14 Intensity Duration Frequency (IDF) curves for planning and design, which do not consider climate change projections that indicate future increases in precipitation volume and intensity. Planning and design of infrastructure that considers these expected increases in precipitation due to climate change will improve the resilience of stormwater infrastructure.

Climate change also poses a risk to current BMPs, most critically affecting water quality goals as outlined by the Chesapeake Bay Total Maximum Daily Load (TMDL). The CSN recommends using a regional approach to promote consistent use of future condition information in the context of projected climate impacts and leading BMP vulnerabilities.

The Challenge

The current standard for most Mid-Atlantic states is based on historic precipitation data (NOAA's Atlas 14 – Volume 2 uses observed data that is twenty years old). In many locations the NOAA Atlas 14 IDF curves underrepresent today's climate conditions. Using outdated precipitation information, compounded by varying design and performance standards across the states and state agencies, results in reduced infrastructure performance and inadequate stormwater policies.

While not all risks to BMPs are directly linked to climate change – proposed development and land use changes, for example – recent observations demonstrate that green infrastructure, conveyance systems, natural ponds and wetlands, and other restored spaces are already strained by increased flows that exceed today's design and performance standards.

These challenges demonstrate the need for updated future precipitation projections to better support and promote regional resilience. However, states and municipalities are facing real-time challenges today, with maintenance and operational needs that require immediate attention. Consideration of future climate change often takes a back seat to the pressing challenges of the present. Limitations in progress also arise from lack of funding, capacity, and guidance. These challenges not only require individual state action, but a greater regionwide framework where capacity is built up across multiple geographies, lessons learned can be shared, and best practices can be scaled up to support regional resilience.

The Approach

To better understand the current state of science, methods, and challenges, CSN initiated a comprehensive review of the state of the practice across the Mid-Atlantic. This review was documented across four reports designed to synthesize climate projections and implications for stormwater design in the region. The effort included a climate survey, review of design standards, climate projections, and a BMP vulnerability analysis. Conclusions and recommendations are presented (see section The Outcome).

In tandem with CSN's efforts, NOAA's MARISA team published the online Mid-Atlantic IDF Curve Tool where projected IDF curves have been developed for multiple stations in the Bay watershed. The tool was driven by the need to evaluate climate change implications on TMDLs at the county level. Data inputs include station-based observations (historical data) and projected precipitation from downscaled climate model ensembles (MACA, LOCA, and BCCAv2) and regional climate models (NA-CORDEX). Outputs consist of IDF curves and future change factors. The baseline for historic data was purposefully selected to align with NOAA's Atlas 14 historical period, 1950-1999. Two future time periods, 2020-2069 and 2050-2099 (i.e., 50-year periods) are available for future projections under the RCP 4.5 and 8.5 climate scenarios.

The tool enables users to search and download individual county scale IDF curve change factors for the 2-year to 100-year storm event (for 5 minute to 7-day durations) within the Chesapeake Bay Watershed and Virginia. Updates to the IDF curves will be made using the upcoming release of the full downscaled CMIP6 archive, more recent rainfall observations, updates to NOAA Atlas 14, and/or technical advancements which improve IDF curve estimation methods.

The Outcome

Over the next three to five years, CSN expects to launch four products to advance regional consistency based on the identified challenges. These efforts will work towards more climate resilient initiatives and provide states with the necessary information to make climate informed decisions. The following provide a high-level description of the future resources.

Vulnerability assessment tool

While some large cities have already completed a climate change vulnerability assessment, most smaller cities have not. This tool will specifically target cities with limited resources and serve as a checklist when reviewing regulatory policies, promoting a better understanding of future climate risks and the next steps to address vulnerabilities.

Expand projections

In many cases, understanding the implications associated with updating future precipitation projections is not straightforward, including deciding between the various climate trajectories and projections, associated uncertainties, and applicable standards. This enhanced decision support tool is anticipated to provide guidance on how to pair the right climate projections to the appropriate application or assessment need (e.g., pairing the most appropriate climate projection(s) with the relevant design or performance standard).

Menu of Resilient BMP Design Adaptations

Current design specifications date back to the early 2000s. Providing a menu of resilient design adaptations will allow states the opportunity to update theirspecifications for the most popular BMP types and increase performances in larger storms.

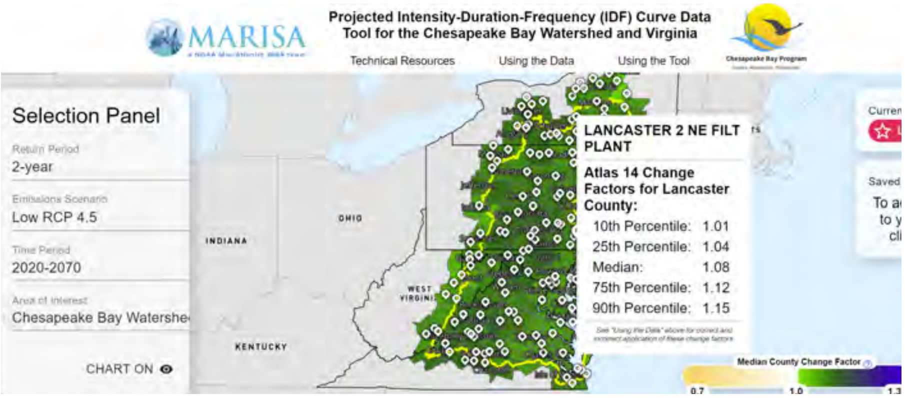
Edit future hydrology with climate change

There are knowledge gaps in understanding how future climate change will impact local hydrologic and hydraulic systems. The effects climate change may have on stormwater and wastewater systems (e.g., effects on influent and effluent) and BMPs (e.g., effects on flow bypass) require further exploration.

CSN's comprehensive review revealed that several states within the Mid-Atlantic region are individually working to address climate change impacts related to stormwater management and/or floodplain protection. Commonalities exist across the several state led efforts, such as completing vulnerability assessments, responding to changes in policy, and developing resources/tools. The following provides examples of select approaches:

Delaware

Since 2012, the state of Delaware has completed a series of sea level rise and vulnerability assessments. Following Executive Order 41 – requiring state agencies to include adaptive strategies that address increasing flood heights and sea level rise within project designs – a guidance document outlining a set of principles and instructions was published by the state. Similar to the MARISA tool, Delaware also produced a Climate Projections Portal where users can assess climate projections based on the CMIP3 and CMIP5 climate model archives.



Return Period: 2-year

Emissions Scenario: Low RCP 4.5

Time Period: 2020-2070

Area of Interest: Chesapeake Bay Watershe

LANCASTER 2 NE FILT PLANT

Atlas 14 Change Factors for Lancaster County:

10th Percentile:	1.01
25th Percentile:	1.04
Median:	1.08
75th Percentile:	1.12
90th Percentile:	1.15

Screen capture of the IDF Curve Data Tool, that provides easy access to IDF projections throughout the mid-Atlantic. (Image from https://midatlantic-idf.rcc-acis.org/, accessed December 29, 2022.)

District of Columbia

The Department of Energy and Environment (DOEE) is taking steps towards climate informed action, including completing vulnerability and risk assessments, assessing climate projections, identifying potential blue-green infrastructure strategies, and developing a climate adaptation plan. DOEE also put forth a framework for climate adaptation focused on transportation and utilities; buildings and development; neighborhoods and communities; and governance and implementation. DOEE is currently studying revisions to current floodplain regulations to account for sea level rise and more intense future storms. DOEE also plans to assess future stormwater performance standards to meet MS4 requirements.

Maryland

In 2021, Maryland's Stormwater Law was updated. It requires the Maryland Departmnet of the Environment (MDE) to report on the most recent precipitation data available, investigate flooding events since 2000, and update Maryland's stormwater quantity management standards for flood control. Maryland has also focused on assessing coastal hazards, including a two-part vulnerability assessment and an interactive map that documents future sea level rise and flood risks. The Eastern Shore Land Conservancy also released an extreme precipitation report that identifies risks associated with the increasing frequency of extreme precipitation events on Maryland's eastern shore. Guidance is provided for local governments seeking to incorporate future stormwater risks into planning and decision-making

Lessons Learned

1. Climate is nonstationary
Historical precipitation data, specifically NOAA Atlas 14 IDF curves, do not reflect today's non-stationary climate. Continued use of existing design standards will likely result in undersized stormwater management infrastructure in the future. Updating NOAA Atlas 14 will be a valuable next step for all communities. This update would increase consideration of future precipitation conditions within stormwater planning and design.

2. States and local governments need updated design standards
The findings of CSN's work highlight responses from practitioners, engineers, decision-makers, stakeholders, as well as climate-related progress in several states. Based on survey responses, there are climate change impact concerns related to both public and private infrastructure. There is also consensus on the need for updated engineering criteria and performance standards that consider future climate change.

3. Uniformity across the watershed is needed
Standards not only vary across states, but they can also differ within departments. There are often differences in how precipitation data is used and considered in planning and design. Developing uniform design criteria and performance standards would promote regional resilience and would also allow for easier sharing of best practices and lessons learned.

4. Guidance and support go beyond analytical needs
States and cities need support developing locally relevant climate projections. Climate projections must also be translated into effective and easily digestible language for decision-makers. Forward thinking decisions require actionable science that directly informs planning, design, and engineering applications. Actionable science can include both qualitative and quantitative formats and is a core facet of the CSN framework. Future tools and applications will best serve under-resourced states and localities if they are published and communicated with this in mind.