Our Changing Precipitation:

A Conversation on the Science of Precipitation and Planning for the Future

A Five-Part Webinar Series January 2022

Hosted by the National Oceanic and Atmospheric Administration and The Water Research Foundation

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Acknowledgments

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SESSION 1

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SESSION 2

Daniel Wright (University of Wisconsin-Madison), **Bilal Ayyub** (University of Maryland and the American Society for Civil Engineers), **Charles Bodnar** (Public Works Stormwater Engineering Center, Virginia Beach, VA)

SESSION 3

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SESSION 4

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SESSION 5

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About the Organizations

The “Our Changing Precipitation” report is the first monograph in a series on climate adaptation by the NOAA Climate Program Office, Climate and Societal Interactions, Adaptation Sciences (AdSci) Program. This specific monograph was done in partnership with the Water Research Foundation, and NOAA’s National Centers for Environmental Information. The monograph series aims to reach a wide audience, including the general public, policy makers, stakeholders, and decision makers.

For further information regarding the “Our Changing Precipitation” monograph, please contact NOAA.ChangingPrecipitation@noaa.gov.

NOAA/OAR/Climate Program Office’s Adaptation Sciences Program (AdSci):
The AdSci program was established in 2021 to advance the knowledge, methods and frameworks to help move society beyond incremental adaptation toward more widespread, connected, adaptive pathways, and resilience strategies with clear economic and societal co-benefits. We expect to accomplish this through a) developing an understanding of key drivers and conditions that shape and enable adaptation across multiple temporal and spatial scales; and (b) identifying key aspects of and promoting opportunities for the use of scientific information to best support preparedness and planned adaptation of high value to social and economic goals.

For further information regarding the AdSci monograph series program, please contact oar.cpo.adaptation@noaa.gov.

NOAA/NESDIS/ National Centers for Environmental Information’s (NCEI) Regional Climate Services Program (RCS):
NCEI’s Regional Climate Services Program provides access to climate information, products, and other resources at regional scales across the United States. Our regional presence provides tailored, comprehensive support to states, communities, and various economic sectors to understand the unique challenges and vulnerabilities created by regional weather and climate conditions. The Program includes Regional Climate Services Directors who engage regularly with stakeholders to increase the value of climate information and support more efficient, cost-effective delivery of products and services. The RCS program supports the Regional Climate Centers, which provides efficient, user-driven data products and services at regional scales.

For more information on climate services at regional scales, please contact ncei.cssd.regionalservices@noaa.gov.

The Water Research Foundation (WRF):
The Water Research Foundation (WRF) is a nonprofit (501c3) organization which provides a unified source for One Water research and a strong presence in relationships with partner organizations, government and regulatory agencies, and Congress. The foundation conducts research in all areas of drinking water, wastewater, stormwater, and water reuse. The Water Research Foundation’s research portfolio is valued at over $700 million.

The Foundation plays an important role in the translation and dissemination of applied research, technology demonstration, and education, through creation of research-based educational tools and technology exchange opportunities. WRF serves as a leader and model for collaboration across the water industry and its materials are used to inform policymakers and the public on the science, economic value, and environmental benefits of using and recovering resources found in water, as well as the feasibility of implementing new technologies.

For more information about WRF, please contact info@WaterRF.org.

This monograph is part of a series on the subject of adaptation by the NOAA Climate Program Office, Climate and Societal Interactions, Adaptation Sciences (AdSci) Program. The AdSci program was established in 2021 to advance the knowledge, methods and frameworks to help move society beyond incremental adaptation toward more widespread, connected, adaptive pathways, and resilience strategies with clear economic and societal co-benefits. Monographs in this series have been prepared to reach a wide audience, including the general public, policy makers, stakeholders, and decision makers. They will each highlight research supported by the Adaptation Sciences Program and its predecessor programs.

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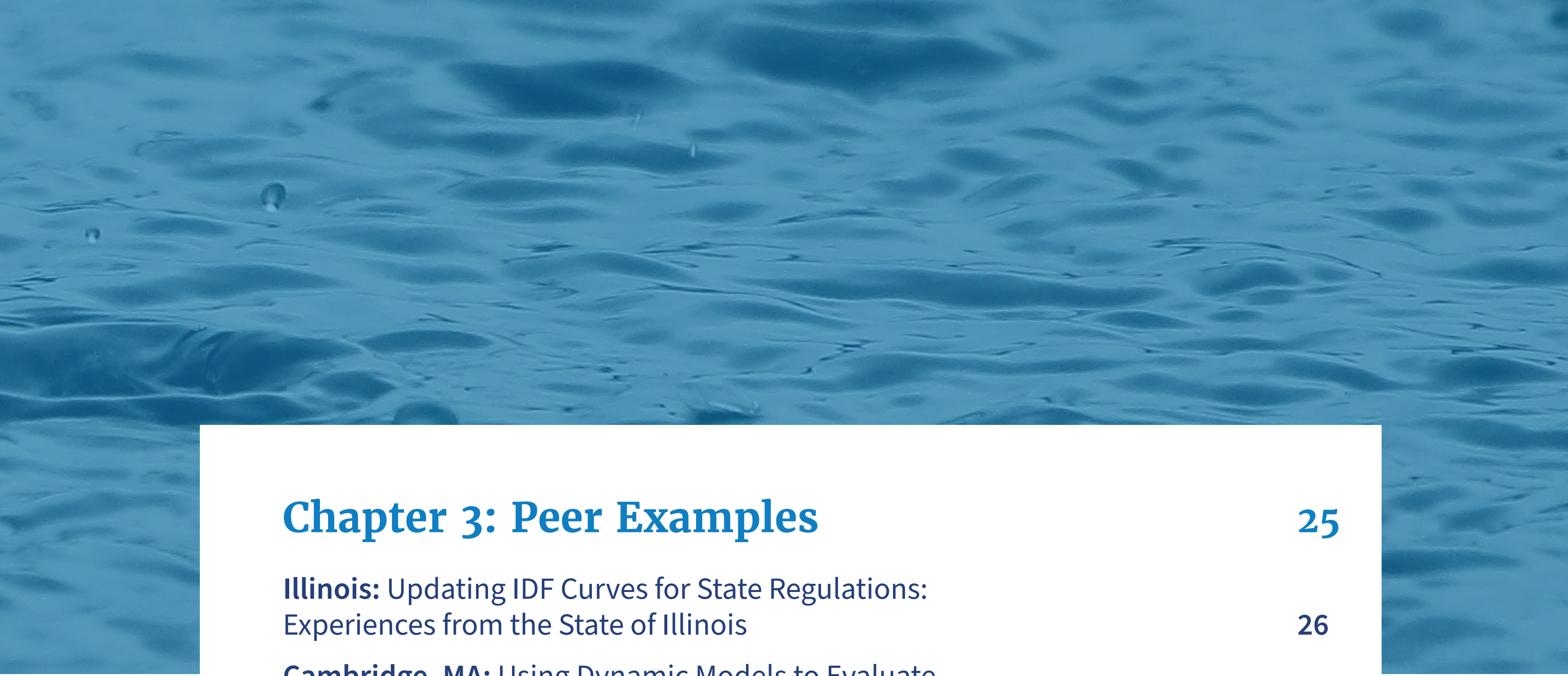

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Summary of Key Messages

AUDIENCE:

Stormwater Managers, Water Utilities, Engineers, and Planners

NOAA continues to develop tools and data to serve the nation's weather and climate needs through research, analysis, and tool development. ↗

One of NOAA's strategic initiatives, the Precipitation Prediction Grand Challenge, aims to improve modeling of the underlying components that constitute earth's climate processes. This earth systems approach will improve our ability to predict weather and climate over various time scales. ↗

NOAA National Weather Service is also working to improve the precipitation frequency data server that many planners and engineers use for designing infrastructure, the current iteration of which is known as Atlas 14. ↗

NOAA's goal for the future is to produce a nationwide update on a regular cycle of ~5-10 years that incorporates nonstationarity that incorporates the latest observations to reflect the most recent trends. Pending necessary funding, NOAA plans to extend and update the entire United States and territories at once (rather than in a piecemeal fashion) in a seamless continuous spatial analysis; and provide a suite of precipitation frequency information that accounts for non-stationary climate assumptions and factors in climate projection information. (Note: as of the writing of this article, the Bipartisan Infrastructure Bill sets aside funding for NOAA to update statistics between 2022-2027. However, pending passage of the Precipitation Act and the Floods Act, NOAA is not yet mandated or authorized to establish a standing, ongoing program for performing this function.) ↗

NOAA has been evaluating ways to update Atlas 14, considering changes in precipitation due to climate change and long term variability. It's recent report provides insight suggesting that climate models are a good tool to account for change in the future climate and that downscaled datasets could be used as a *relative change* between the present and the future precipitation frequency estimates. ↗

NOAA also suggests that, given the issues with projecting both the future emissions scenarios as well as underlying precipitation modeling errors, the model-based precipitation frequency estimates *should not be used in design as absolute values*. ↗

Improved precipitation data and methods from NOAA is essential, but the problem does not lie only in NOAA's hands. The engineering community, too, is working to revise methods for risk assessment and planning for uncertainty. ↗

Engineering standards setting bodies such as ASCE are developing guidance for analyzing risk and designing infrastructure, but accepted consensus standards are years away. ASCE 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, is not due to be updated until 2028, for example. ↗

The Transportation Research Board, supported by USDOT projects NCHRP 15-61 and NCHRP 20-44(23), is also evaluating new methods for using downscaled climate models in hydrologic assessment. ↗

Meanwhile, communities are engaging with engineering firms and academic researchers to evaluate risk and inform local decision making. In many cases, decisions cannot be delayed as their aging infrastructure requires upgrades to meet water quality, public health, and flood protection goals, or new development proceeds in areas at risk. The practical challenge for managing stormwater and flooding can be examined through three lenses: ↗

- evaluating precipitation (understanding the current trends based on observational data and/or understanding the future probabilities based on climate projections).
- understanding how well infrastructure performs under various scenarios.
- navigating resource challenges while redressing key vulnerabilities and getting to buy-in to be able to implement new codes, standards, and practices.

While there is still no consensus on an approach for anticipating future extreme precipitation, practitioners and consultants find that there is value in conducting these analyses. Using one or more methods or models are useful for the results themselves and for creating the opportunity to have conversations. Several analysts advocate for use of multiple approaches which can form the basis for well-informed local decision making. ↗

Given the changing nature of precipitation and the difficulties of projecting future changes, planners should periodically revisit data and methods to validate findings or recalibrate policies as needed. ↗

There are three general approaches for evaluating future precipitation, which can be characterized very briefly: ↗

1. **Apply Past Trends to the Future:** Update rainfall statistics using shorter and more recent data set with as spatially detailed rainfall radar data as can be obtained or giving more weight to data collected in more recent time periods and extrapolate results to the future.
2. **Use Semi-Empirical Methods:** Methods such as statistical weather generators use observed climate data to simulate changes in variability and changes in mean climate to create plausible future scenarios. The results can be used to test the performance of infrastructure.
3. **Apply Downscaled Global Change Models (GCMs) to Historical Statistics:** Extract precipitation projections from one of the most common data sets (e.g., LOCA, BCCAv2, or NA-CORDEX) and fit the statistical distribution of recent rainfall to the future projections.

With the advent of climate change, modelers are adopting a range of new and updated methods to evaluate system performance such as by using improved or dynamic hydrologic and hydraulic (H&H) modeling, decision scaling, and risk management. ↗

While related to rainfall, flooding cannot be directly correlated to precipitation. Stormwater managers have long used H&H models to design systems to manage certain amounts of rainfall and drainage as stipulated by federal water quality regulations or by engineering practices embedded in federal, state, and local codes and standards. ↗

Methods being used by some communities to evaluate system performance and identify vulnerabilities include: ↗

4. **H&H Modeling:** To improve H&H models, modelers need to identify emerging flooding hot spots, gather finer spatial & temporal resolution data, and improve the physical representation of the installed conduit system. Some communities have designed dynamic two-dimensional H&H models.
5. **Decision Scaling and Stress Testing:** For resource-limited communities, decision scaling or stress testing helps to focus attention on the parameters of specific decisions. By first understanding the conditions that make the system vulnerable, it is possible to evaluate the results of increased stressors such as peak intensity or peak volume.
6. **Risk Management:** Apply probabilistic methods for quantitative risk analysis and develop low-regret, adaptive strategies to make a project more resilient to climate change.

AUDIENCE:

State and Local Decision Makers

State and local policy makers know they must find ways to get buy-in to significant changes in policies and practices.

Practitioners discussed three elements: the need to re-evaluate the basis of codes and standards, engaging the public for increased understanding and buy-in, and paying for infrastructure while addressing historical inequities. ↗

Even before new standards are in place for managing stormwater and urban runoff, States and localities would be prudent to review existing codes, regulations, policies, and data sources to ensure that infrastructure and communities are as resilient as possible as we move toward an uncertain future. While this is especially urgent in communities that are still relying on information that has not been updated for more than 50 years, such as TP40 or Atlas 2, it is also relevant to those using early versions of Atlas 14 that date back 20 years or may have been adopted prior to increases in urban density and before impacts of climate change became more noticeable. ↗

While there is still no consensus on an approach for anticipating future extreme precipitation, there is value in conducting analyses and convening dialogue. Using one or more analytical methods are useful for the results themselves and for creating the opportunity to have conversations. Several analysts advocate for use of multiple approaches which can form the basis for well-informed local decision making. ↗

In addition, given the changing nature of precipitation and the difficulties of projecting future changes, planners should periodically revisit data and methods to validate findings or recalibrate policies as needed. ↗

Getting buy-in from the community and decision makers can take time but progress can be made by engaging stakeholders at each stage. Getting public buy-in to change can be expedited by ensuring data is transparent, understanding residents' experiences with new flooding, engaging them in documenting impacts and finding solutions, and conveying concepts such as the true meaning of terminology (for example that the 100-year storm can, in fact, occur more frequently). ↗

To move the nation toward resilience, the bipartisan infrastructure bill allocates massive amounts of funding for communities over the next 5 years, providing an opportunity to consider impacts of climate change in infrastructure design. ↗

It is well documented that disadvantaged communities bear disproportionate impact from climate change, compounding existing vulnerability. Under the Justice 40 initiative, 40% of benefits from federal investments in "covered programs", addressing topics such as climate change and clean water infrastructure, should be directed at disadvantaged communities.

AUDIENCE:

NOAA, USDOT, USEPA

Climate change is disrupting the well-honed balance and long-standing practices for managing stormwater as evidenced by widespread impacts in cities nationwide.

How can NOAA respond to community managers who are confronting the current and future impacts of climate change on stormwater management systems?

- **Continue internal engagement.** While NOAA works on long-term improvements in precipitation observations and models, coordination and engagement by and among OAR/CPO, NESDIS/NCEI, and the NWS/OWP are essential for ensuring programs and services are engaged, relevant, and timely in providing assistance to build resilience nationwide.
- **NOAA product updates and technical assistance are needed.** Participants indicated that communities are relying on consultants and academics but need NOAA's technical assistance to build their capacity to address these issues. Help is needed on several aspects of the issue:
    1. timely updating of Atlas 14 or its equivalent;
    2. incorporating nonstationarity using observational data;
    3. considering future climate change and conducting risk assessments for planning long-lived infrastructure; and
    4. improving accuracy of climate models for precipitation predictions.

- Update NOAA's Atlas-14 and related products. State and local planners are urgently calling for NOAA to update Atlas 14 or its successor as it is the authoritative source for precipitation statistics cited in state and local codes nationwide for designing stormwater and other water infrastructures. States, water utilities, and engineering firms want NOAA to continue to be an authoritative source by improving availability and use of precipitation statistics in three ways:
    1. Update NOAA Atlas 14 (or its successor) nationwide at least every 5–10 years using the most updated observations;
    2. Update NOAA Atlas 14 methodology to incorporate nonstationarity; and
    3. Provide guidance on evaluating future statistics under climate change, for mid-century and end-of century.
- Convene scientists on methods and best practices for incorporating non-stationarity. Many communities are engaging consultants to perform this function using various methods. NOAA needs to convene and connect with the various researchers to develop and jointly message best science and practices. These best practices are critical to deliver NOAA services to help communities make informed decisions on ways to build resilience to changing precipitation patterns.
- Engage with practitioners on best practices for evaluating precipitation under future climate change. Planners and decision makers understand that downscaling future climate change and predicting rainfall patterns include uncertainties, especially for the spatial scales needed by communities. Many states and localities are engaging consultants to help them assess their risks and exposures under future climate scenarios. NOAA's engagement with practitioners can help communities navigate this challenge and help develop best practices.
- Improve precipitation prediction. The research community needs support to expedite improvements in observations and models in hopes that future projections of precipitation become more reliable, as recognized and outlined in NOAA's Precipitation Prediction Grand Challenge. The goals of Precipitation Prediction Grand Challenge are welcome by water resource practitioners, but the timeline for results is not compatible for current decision-making. At the same time, the community understands that better observations are needed to support the underlying models.

- **Deliberately practice co-development of products and services with communities that will use them.** Including communities in the beginning, middle and end of the development of products and services will help shape the final products and services available to users. Their experience will also help manage expectations, improve understanding, and ultimately improve the likelihood of their application and use of the product.
    - Invest in continuous engagement with communities. Participant feedback for this webinar series was overwhelmingly positive, with many suggesting that

this type of engagement and two-way conversation with experts helped them understand the state of the science, what the government is working on, and how to think about ways to apply information locally.

- Regular updates to improve tools and methods: Method improvements are being tested and adopted by various state and local jurisdictions, all of which carry validity in the context of informing local decision making. NOAA can continue to document these methods and facilitate peer-to-peer learning while keeping stakeholders informed of NOAA's ongoing improvements.
- NOAA, USDOT, and USEPA are key federal agencies involved with stormwater management and provide information on different aspects of the problem (e.g., NOAA provides rainfall data and statistics. USDOT provides guidance and programs for designing urban drainage, USEPA regulates water quality). Participants in these webinars suggested that these entities also be engaged in these inter-disciplinary processes to not just provide new statistics, but to also co-create interim methods for understanding change and planning for the future.

- **Understand the context.** Management of stormwater involves federal, state, and local agencies and nongovernmental organizations concerned with water quality, urban drainage, and flooding.
  - Voluntary standards-setting bodies such as the American Society of Civil Engineers (ASCE) provide technical specifications for engineers designing infrastructure.
  - Standards setting bodies are also proceeding to develop their own approaches given the immediacy of the problem. However, this too is a years-long process for adoption of consensus standards. For example, ASCE 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, is not due to be updated until 2028, for example.
  - When NOAA updates the Precipitation Frequency Data Server with new statistical products such as Atlas 14, it can take several years for the new data to be propagated into State and local codes, standards, and practices.
  - Some state and local data users are relying on consultants and academics for assistance. Some are developing their own statistical analyses using more recent data, some are examining projections using climate modeling, and some are conducting a variety of sensitivity analyses and vulnerability assessments for policies and planning. This has resulted in a lack of consensus on methods for accounting for non-stationarity across the US.

Chapter 1:

INTRODUCTION TO THE CONVERSATION

Why This Series?

NOAA Climate Program Office (CPO) and National Centers for Environmental Information (NCEI) have been working with stakeholders in the water sector for more than 15 years.[1] This work has led to a greater understanding of the research needs of water utilities and local planners who require near- and long-term information on weather, climate change, and changes in precipitation.[2] In this 5-part webinar series (held during September and October, 2021), NOAA and its partner, the Water Research Foundation, focused on stakeholder interest in understanding how to plan for changes in precipitation that affects stormwater and urban flooding.[3]

As of 2018, the U.S. Census Bureau estimated there is $1.3 trillion worth of infrastructure in the U.S. (including bridges, buildings, power plants, etc.) — and most are likely to not be designed to account for a changing climate. With a design life of 50 or 100 years, or even longer, these projects are going to experience greater hazards and more extremes than for which they are designed.[4]

One area that has not received as much attention in the climate resilience community (compared to other types of infrastructure designed to manage extreme flooding or sea level rise) is infrastructure that manages smaller storms, such as stormwater and urban drainage systems. While not considered as a source of catastrophic risk, they are essential to health, safety, and economic well-being. Communities nationwide are experiencing increases in amounts of precipitation, flooding homes and businesses, damaging roads, bridges, and underground infrastructure, causing sewer overflows that result in water quality problems, flooding of crops, and more.

Source: NOAA

Perhaps not surprisingly, more than 2,000 people registered for the series and more than 1,500 unique viewers participated in one or more of the five webinars. Participants included state and local governments, consultants and engineering firms, academic researchers, as well as other federal agencies. The feedback received was overwhelmingly positive — it is evident that this series responded to a clear and present need.

1 Please see the 2019/2020 Water Utility project website at: https://cpo.noaa.gov/Meet-the-Divisions/Climate-and-Societal-Interactions/Water-Resources/Water-Utility-Study and the Water Resources Dashboard at: https://toolkit.climate.gov/topics/water/water-resources-dashboard.

2 Please see the summary of Research Needs resulting from the 2019/2020 Filling the Gaps Study at: https://cpo.noaa.gov/Portals/0/Docs/Water-Resources/CPO-4Pager-September-15-2021-Final.pdf

3 While this series is focused on precipitation and stormwater, the issues raised are relevant for all water management sectors, including design and management of drinking water and wastewater infrastructure, combined sewer systems, flood management, etc.

4 Bilal Ayyub: "At the Crossroads of Civil Engineering and Climate Change", https://www.linkedin.com/pulse/crossroads-civil-engineering-climate-change-dan-tobin

Webinar Format

To advance the national conversation about how to address the issue of stormwater and urban drainage, this series was designed with three goals in mind:

1. to help the public understand the issues with modeling recent and future local scale precipitation;
2. to shed light on federal agencies, academic researchers, and the engineering community that are working to develop information and methods to support efforts to build resilience;
3. to facilitate mutual understanding between scientists, engineers, state and local decision makers, data providers, and data users; and
4. to illustrate how communities are working to fill the information gap as they undertake adaptation despite the complexity of modeling the future.

Factoring in stakeholder preferences to learn from peers in addition to scientists, this series was intentionally structured with water utility managers facilitating each session and 'interrogating' scientists and experts to maximize relevance for the participating audience. In webinars 1 through 4, experts presented information, followed by questions and dialogue facilitated by a water utility practitioner. Webinar 5 featured four peer case studies, with facilitation by a scientist/consultant. This format maximized relevance to the intended audience.

This document represents a brief summary of the presentations and characterization of the main ideas raised by participants.

Major Challenges for Managing Precipitation

To understand the challenge, we can break the issue into three interrelated components: 1) precipitation data, statistics, and modeling; 2) hydrologic and hydraulic modeling and engineering practices; and 3) policy hurdles including financing and equity, codes, and standards, and getting community buy-in.

"Very useful and timely. I have been talking about some of the topics for a decade or more, and it is terrific that these topics are being more widely discussed, especially brought to practitioners. Thank you."

Evaluating Precipitation (past and future): NOAA is widely viewed as the authoritative source for weather and climate information, including precipitation statistics as served up through NOAA Atlas 14 and related documents. Unfortunately, there is currently a vacuum in light of changes in precipitation being felt nationwide. The genesis of unmet needs can be summarized as 1) a lack of funding for NOAA to provide timely updated statistics based on the most currently available data; 2) the past use of statistical methods that do not account for nonstationarity, a scientific understanding that has been part of the conversation in the adaptation community since a 2008 article by Milly et al;[5] 3) the fact that projecting future changes in local scale precipitation as a result of climate change is problematic at best; and 4) the lack of guidance to communities on how to consider future climate change when planning long-lived and often very expensive infrastructure. NOAA is working on revising its methodologies, but it will take time before new updated statistics are nationally available, and it is unclear if and when NOAA will be able to provide guidance for evaluating future, local-scale precipitation. NOAA's Precipitation Prediction Grand Challenge also brings hope for improved forecasts but the fruits of that endeavor for local decision makers are years away.[6]

Evaluating Performance of Stormwater and Drainage Systems: Improved precipitation data is essential, but the problem does not lie only in NOAA's hands. The engineering community, too, finds itself at a crossroads. Communities are experimenting with different ways to evaluate risk and design infrastructure capable of managing risk of flooding in the near-

5 Milly, Paul, et. al.. (2008). Stationarity Is Dead: Whither Water Management?. Science. 319. 573–574.
6 Several bills under consideration by the 117th Congress could improve the funding status of these programs.

"We are exploring adding these methods ... and before we bring these methods to the public and start education models on them, we need to really do our homework and these webinars couldn't be more perfectly timed for our needs. Thank you!"

and long-term using a combination of green and gray infrastructure. Many local jurisdictions feel that this is the more practical approach for action now as witnessed by increased focus and development of these types of structures — but it is still rife with guess work in light of the lack of sanctioned engineering guidance on evaluating future precipitation. In response to these felt needs, several standards setting bodies are beginning to work toward developing such guidance, including ASCE.[7] Again, it will take some years before this issue is settled.

For both issues (providing precipitation data as well as engineering guidance), practitioners are increasingly looking to the private sector and academia. One academician calls it the wild wild west until authoritative sources are agreed upon.

Policy Hurdles: Solving local issues is as much a policy endeavor as an engineering endeavor involving agreeing on new codes and standards, getting community buy-in, and funding projects including redressing historical inequities. Amending federal, state, and local codes and standards and engineering guidance will require the respective authorities to undertake careful reviews to not only find sound methods but to also ensure that regulations and ordinances reflect the best available information, including consideration for integrating practices across department silos. Meanwhile, obtaining buy-in for new codes and standards, for financing infrastructure, for redressing inequities, etc., will require concerted public engagement that demonstrates the benefits of adaptation and gets their input into solutions. Upgrading infrastructure (including both new development as well as retrofitting aging infrastructure) can be costly. Fortunately, the bipartisan infrastructure bill will provide a large infusion of funds for communities over the next 5 years, including for the most disadvantaged and vulnerable communities. In other words, addressing the policy and socio-economic factors will be just as challenging as conducting the necessary hydro-climatic analyses.

Conclusion: More scientific and engineering discovery is needed and making information practical and usable requires three-way engagement between scientists, engineers and decision-makers, and the public. The challenge is upon us now; responding to the challenge will take years. Meanwhile, we can all learn from the front-line communities that are acting now.

Modeling Precipitation — State of the Science

At large scales, an increase in extreme precipitation is one of the most confident projections of climatic changes expected to result from global warming. Models consistently project that temperature increases everywhere, extreme daily precipitation increases almost everywhere (10–30% for the continental U.S.), and generally the tropics and high latitudes will be wetter, and the subtropics will be drier. We asked the scientists, has CMIP6 improved the ability to project regional scale precipitation? The answer is that the findings from CMIP6 and the quadrennial U.S. National Climate Assessment since 2000 are similar to earlier climate model simulations due to basic physics.[8]

- The maximum amount of atmospheric water vapor increases rapidly with temperature
- The atmosphere in a warmer world can hold more water vapor

7 The new ASCE 7 will not be updated until 2028, meanwhile, it does not include treatment of climate change. Other committees are at work on how to consider climate change in engineering. See: https://www.asce.org/search#q=climate%20change&sort=relevancy

8 Kenneth Kunkel, Research Professor and Lead Scientist for Assessments, NOAA Cooperative Institute for Satellite Earth System Studies. North Carolina State University Institute for Climate Studies; and
Jin Huang, Chief, Earth System Science and Modeling Division, NOAA Climate Program Office, and Wayne Higgins, Director, Climate Program Office, NOAA Oceanic & Atmospheric Research

- There is more “fuel” for those meteorological systems capable of producing extreme precipitation
- Research shows that the most important factor affecting extreme precipitation magnitudes is the amount of water vapor

Why hasn’t modeling of future local scale precipitation improved in more than 20 years? Precipitation forecasts have, in fact, improved but it has been slow (slower than improvements in hurricane intensity forecasting skill, for example). Predicting precipitation especially at the local scale is difficult because weather models and climate models have common systematic errors in underlying physical processes. Recognizing the societal imperative for improved predictions, NOAA has undertaken a Precipitation Prediction Grand Challenge (PPGC). PPGC aims to provide more accurate, reliable, and timely precipitation forecasts across timescales that are most practical for specific societal applications by improving in three categories: sources of predictability; physical processes and biases; and modeling and observational strategies.[9]

Meanwhile, NOAA has been studying methods for considering future climate change in its calculation of precipitation frequency statistics used for designing infrastructure design and risk assessment. A recent report[10] provides insight suggesting that climate models are a good tool to account for change in the future climate and that downscaled datasets could be used as a *relative change* between the present and the future precipitation frequency estimates. However, given the underlying precipitation modeling errors and the issues with projecting both the future emissions scenarios, the model-based precipitation frequency estimates *should not be used in design as absolute values*. In addition, providing a probability range among various downscaled datasets may better characterize the uncertainty associated with climate model predictions. Meanwhile, climate models at hourly durations require further investigation.

NOAA’s work on the Precipitation Prediction Grand Challenge and its efforts to improve methods for calculating precipitation statistics using both observed and modeled rainfall will help meet society’s need for actionable science and service. Unfortunately, communities are already facing impacts of climatic change and are needing to find ways to inform decisions before NOAA’s work is complete.

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9 Jin Huang, Chief, Earth System Science and Modeling Division, NOAA Climate Program Office, and Wayne Higgins, Director, Climate Program Office, NOAA Oceanic & Atmospheric Research

10 *Analysis of Impact of Non-stationary Climate on NOAA Atlas 14 Estimates: Assessment Report*, National Weather Service Office of Water Prediction, Jan. 31, 2022. https://hdsc.nws.noaa.gov/hdsc/files25/NA14_Assessment_report_202201v1.pdf.

Chapter 2:

THE IMPLEMENTATION CHALLENGE

NOAA Atlas 14 has traditionally been the gold standard for obtaining statistical data for designing infrastructure. However, until it is updated, that can no longer be said given the changing patterns of precipitation. Many stormwater and drainage systems are being overwhelmed, especially by the trend for more intense rainfall over shorter durations. Practitioners are looking for guidance wherever they can find it on how to plan for the future. The practical challenge for managing stormwater and flooding can be examined through three lenses:

- evaluating precipitation (understanding the current trends based on observational data and/or understanding the future probabilities based on climate projections).
- understanding how well infrastructure performs under various scenarios.
- navigating resource challenges while redressing key vulnerabilities and getting to buy-in to be able to implement new codes, standards, and practices.

Conversations with modelers, engineers, and federal, state, and local practitioners reveal a variety of analytical and practical approaches useful for others, depending on availability of expertise and resources.

Evaluating Precipitation (past and future)

While there is still no consensus on an approach for anticipating future extreme precipitation, there is value in conducting these analyses. Using one or more methods or models is useful not only for the results themselves but in the opportunity it creates to have conversations. In fact, using a diversity of methods can reveal uncertainties across data sources that should be considered. Several analysts advocate for use of multiple approaches which can form the basis for well-informed local decision making.

Very briefly, there are three basic approaches for evaluation of precipitation in which the speakers'[11] experiences fall, each with some variation and which can be used in combination with each other.

Applying Past Trends to the Future

- Update rainfall statistics using shorter and more recent data sets (potentially including spatially detailed rainfall radar data) or giving more weight to data collected in more recent time periods.
- A variation of this is to apply a factor change/delta method to NOAA Atlas 14 for future time periods.
- Apply NOAA Atlas 14 methods to update statistics more frequently to capture changes.

CASE STUDY:

Illinois State Water Survey

For their revised Bulletin 75 (2020), Illinois used data collected during the 70 year period between 1948-2017 to better represent their current, wetter climate and gave more weight to the second half of the record (1983-2017) that showed a 5% increase over the first half. The result in the northern part of state with 90% of Illinois' population and infrastructure was striking. The old TP-40 (1961) had indicated that the 100-yr., 24-hr. storm was 4 inches; Bulletin 70 (1989) showed 7.58 inches; and Bulletin 75 (2020) showed 8.57 inches. Under-designed infrastructure was causing the extra inches to become pure run off.

11 Daniel Wright, Assistant Professor, Civil and Environmental Engineering, University of Wisconsin-Madison; Co-Chair and Science Advisory Board member, Wisconsin Climate Change Initiative Infrastructure Working Group

- Use current NOAA Atlas 14 values but select a higher design storm recurrence interval. Some communities conduct various analyses to understand some of the ranges of future possibilities, but then choose to simply apply more stringent NOAA Atlas 14 values. For example, using a 5-year storm instead of a 2-year storm, or a 500-year storm instead of 100-year.

Using Semi-Empirical Methods

- Statistical weather generators use observed climate data at a location to generate random numbers to generate a sequence of weather. This method does not forecast climate change; rather, they are designed to simulate changes in variability and changes in mean climate to create plausible scenarios. The results can be used to test the performance of infrastructure.

CASE STUDY:

Welland, Ontario, CA

The City of Welland, Ontario conducted a climate vulnerability assessment of their stormwater, sanitary sewer, and wastewater systems. Analysts used a delta change approach based on CMIP3 to look out to 2050, a modest $20,000 effort. The City then examined the influence of the various IDF rainfall relationships on the design of stormwater management end-of-pipe and conveyance systems and evaluated the implications of changing the existing 2-year design criterion for storm sewers to a 5-, 10- or 25-year return period to account for future rainfall. The findings were dramatic. They found that by 2050 they would need to increase the system's maximum volume by 89%, and that updating pipes by 1 increment would cover almost all future rainfall at an incremental cost.

- Storm transposition is a method to take a storm that has occurred in a nearby area and evaluate what would have happened if it occurred in a critical area of the watershed. (We have all experienced cases where we breathe a sigh of relief for dodging the proverbial bullet of a major forecasted storm that landed elsewhere.)
- Use of the historical record and analogue events is similar to storm transposition. Some communities have looked back into the historical record for worst case events that occurred under natural variability, sometimes even looking into the paleorecord. Given the changes in land use, the method can inform evaluations of system performance.

Applying Downscaled Global Change Models (GCMs) to Historical Statistics

- Evaluate downscaled data sets to estimate future rainfall statistics. Three commonly used data sets are LOCA, BCCAv2, and NA-CORDEX. The University of Wisconsin's UWPD has also been used.[12]
- Extreme value analysis of climate model projections and applying the factor change concept/delta method to NOAA Atlas 14 based on future relative to the past statistics.[13]
- The steps in these methods are:
    - Develop current rainfall distribution (e.g., gather observed rainfall data for your chosen period of record and fit a statistical distribution).
    - Estimate future extreme rainfall (e.g, select a downscaled GCM database, extract precipitation data, compute the ratio of future storms to the historical record obtained in step 1).
    - Extract ensemble statistics (multiply the current NOAA Atlas 14 by the delta change factor for each return period and apply spatial interpolation and smoothing across the landscape. A less optimal option would be to use the downscaled statistics directly for design purposes).

12 Wu, S., et. al.. *A Comparative Analysis of the Historical Accuracy of the Point Precipitation Frequency Estimates of Four Data Sets and Their Projections for the Northeastern United States. Water* **2019**, 11, 1279. https://doi.org/10.3390/w11061279: https://www.mdpi.com/2073-4441/11/6/1279

13 Ragno, E., et. al. (2018). *Quantifying changes in future Intensity-Duration-Frequency curves using multimodel ensemble simulations.* Water Resources Research, 54, 1751–1764: https://doi.org/10.1002/2017WR021975; https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017WR021975

CASE STUDY:
Cambridge, MA

The City of Cambridge, MA, conducted a vulnerability assessment that incorporated projections based on climate scientist Dr. Katherine Hayhoe's statistical downscaling. The downscaled projections were adjusted for the extreme value distribution based on the 30-year periods with midpoints in 2030 and 2080. This resulted in the statistics needed for designing infrastructure from the 2-year storm to the 100-year. While the current NOAA Atlas 14 data indicates that Cambridge's 100-year, 24-hour storm is 8.9 inches, the city found that in 2030 it is likely to be more than 10 inches and in 2070 almost 12 inches. These values are similar to the current 500-year storm. The results also enabled Cambridge to compare new citywide flood maps to the FEMA flood zones. The newly developed flood maps are now being used in city ordinances for all new development.

Update on NOAA Atlas 14

NOAA Atlas 14 is one of the most important and valuable tools we have available to us for precipitation frequency estimation as an input in sizing engineering infrastructure and assessing the severity of extreme storms events. It is incorporated into federal, state, and local codes and standards that are used by engineers and regulators. However, the current NOAA Atlas 14 methodology assumes climate stationarity — an assumption that is undercut by climate change. Also, the current funding model presents challenges to timely volume updates, which are done on a region-by-region basis spanning several decades. (Note: as of the writing of this article, the Bipartisan Infrastructure Bill sets aside funding for NOAA to update statistics between 2022–2027. However, pending passage of the Precipitation Act and the Floods Act, NOAA is not yet mandated or authorized to establish a standing, ongoing program for performing this function.)

NOAA has been evaluating new methods for updating NOAA Atlas 14 and related documents supported by multiple university research efforts. However, adopting a new method is just the first step that will take time in itself; calculating the values nationwide will take not only money but time as well. Propagation of new statistics into federal, state, and local code is also a multi-year process. Until the situation settles, communities who cannot wait are proceeding with their own methods, some of which are described in this webinar summary. The recent results of the NOAA study, however, can give some insights that might help practitioners in the meanwhile.

NOAA's goal for the future is to produce a nationwide update on a regular cycle of ~5–10 years that incorporates nonstationarity that incorporates the latest observations to reflect the most recent trends. Pending necessary funding, NOAA plans to extend and update the entire United States and territories at once (rather than in a piecemeal fashion) in a seamless continuous spatial analysis; and provide a suite of precipitation frequency information that accounts for non-stationary climate assumptions and factors in climate projection information.[14]

As mentioned in the introduction, NOAA's recent report[15] provides insight suggesting that climate models are a good tool to account for change in the future climate and that downscaled datasets could be used as a relative change between the present and the future precipitation frequency estimates. However, given the issues with projecting both the future emissions scenarios as well as the underlying precipitation modeling errors, the model-based precipitation frequency estimates *may not be adequate as absolute values, particularly for the wide range of NOAA Atlas 14 design applications*. In addition, relying on one downscaled dataset does not account for the variability among the future projections; providing a probability range among various downscaled datasets may better characterize the uncertainty associated with climate model predictions.

14 Mark Glaudemans, P.E., Director, Geo-Intelligence Division, NOAA Office of Water Prediction

15 *Analysis of Impact of Non-stationary Climate on NOAA Atlas 14 Estimates: Assessment Report*, National Weather Service Office of Water Prediction, Jan. 31, 2022. https://hdsc.nws.noaa.gov/hdsc/files25/NA14_Assessment_report_202201v1.pdf.

“Fantastic, important. I’ll be referring back to each of the webinars and adopting practices and methodologies that you’ve presented. The speakers’ knowledge and congenial attitudes made this series outstanding. Thank you.”

Evaluating Performance of Stormwater and Drainage Systems

While related to rainfall, flooding cannot be directly correlated to precipitation. Flooding involves various parameters such as design of stormwater and drainage structures, impervious land cover, soil conditions (moisture, snow, frozen soil), agricultural practices, diversions by dams, reservoirs, and lakes, etc. There are also different kinds of floods — riverine flooding, overland surface flooding, groundwater flooding, sea level rise and coastal flooding etc. Stormwater managers have long used hydrologic and hydraulic (H&H) models to design systems to manage certain amounts of rainfall and drainage as stipulated by federal water quality regulations or by engineering practices embedded in federal, state, and local codes and standards. These have always been based on the historical record along with local decision making for risk management to meet public expectations for levels of service.

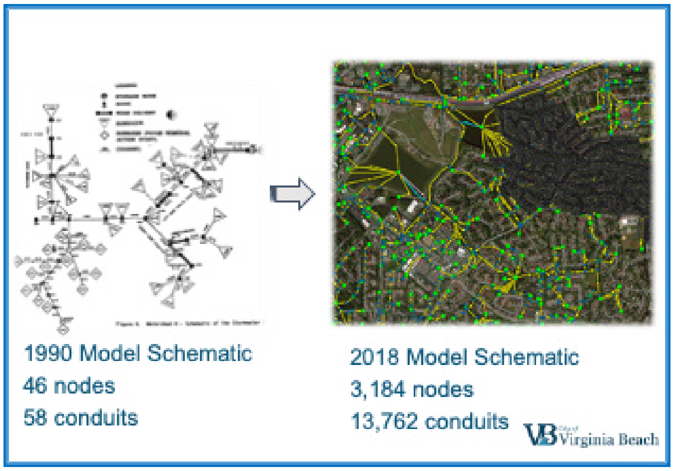
In growing recognition of climate change, modelers are adopting a range of new and updated methods to evaluate system performance such as improved or dynamic H&H Modeling, decision scaling, and risk management.

H&H Modeling

Hydrologic models represent surface flow processes (rainfall, infiltration, evaporation, runoff generation) while hydraulic models portray the fluid dynamics and mechanical behavior of water as it flows through drains, inlets, pipes, and over weirs. Common Industry Standard H&H Models include EPA Stormwater Management Model (SWMM) and proprietary derivatives (PC-SWMM, XPSWMM, InfoSWMM, etc.). Other models such as MIKE URBAN, HEC, etc. are also in common use.

Key simplifications and assumptions are associated with model construction, calibration, and validation such as parameterization that uses assumed values to represent landscape and storm properties, subcatchment aggregation at a spatial scale to represent the hydrologic elements of the model as simply as needed; and conduit skeletonization to represent the physical elements of the hydraulic system. After the model has been constructed it undergoes verification (to check that the results make physical sense); calibration to tune model properties to reasonably represent known historical conditions; and validation to quantify the accuracy of the model by simulating other known historical conditions.[16]

To improve H&H models, modelers need to identify emerging flooding hotspots and gather finer spatial and temporal resolution data (precipitation, physical attributes of the drainage system in flooding hot spots, measurements of inflow and infiltration, and accuracy of water table elevation relative to inverts of drainage infrastructure). It is particularly important to improve the physical representation of the installed conduit system, as the smaller conduits may have been skeletonized out to simplify the model — but assuming that only the big pipes matter limits our ability to examine localized flooding. A model that reasonably represents pollutant loading or combined sewer overflow (CSO) frequency may not be able to represent flood patterns and frequencies unless the model is filled in to include the smaller conduits.



Source: Sea Level Wise, City of Virginia Beach Department of Public Works

16 Franco Montalto, P.E., PhD, The Sustainable Water Resource Engineering Laboratory, Drexel University

CASE STUDY: Boston, MA

When Hurricane Harvey hit Houston the Mayor of Boston asked, what if that happened here? To evaluate potential impacts in 2030 and 2070, the utility upgraded its H&H model to a two-dimensional dynamic sewer and drain model. The model is fed by data based on various sizes and types of storms that have occurred historically and integrated a dynamic coastal model. A mesh enables visualization of how water spreads across the landscape and how it interacts with the city's sewer system. An interactive model viewer interface visually conveys just what the numbers mean in the city, showing a 360-degree 'google earth' style view at the streetscape level. The model shows the location of critical facilities that could be affected and helps conveys information on how water could flow inland from sea level rise and a storm surge event.

CASE STUDY: Portland, OR

City of Portland, OR analysts conducted a sensitivity analysis for an area of the city that was experiencing increases in basement flooding. Analyst 'stressed' the modeled system by making changes to the simulated rainfall event (the design storm). On one scale, they varied peak intensity of precipitation over the baseline — from 10% to 50% more intense (in increments of 10%) — and on another scale they varied the peak volume of precipitation over baseline — also 10% to 50% greater volume. Lesson learned? The system was more susceptible to intensity than to volume, but the worst-case scenario was a combination of the two. Staff were already aware of the higher sensitivity to intensity but had not explored how much additional risk manifested in the system as that intensity increased. The analysis showed which parts of the system are likely to be the first to experience new risk, suggesting an order in which climate resilience projects should be pursued.

Some communities, such as Boston and Cambridge, have designed dynamic two-dimensional H&H models. These models examine the impact of various types and sizes of storms including the interplay with coastal flooding, as it interacts with the city's water management infrastructure. Dynamic models can include visualizations to help the public understand implications of flooding under different scenarios.

Decision Scaling and Stress Testing

Trying to figure out how to account for the future may be beyond the resources of some communities but getting to action in the face of deep uncertainty is still possible. One approach — decision scaling[17] — focuses attention on the parameters of specific decisions. First, understand the conditions that make the system vulnerable, and the level of concern associated with those vulnerabilities. Then, evaluate alternative ways to reduce vulnerability and identify which options perform well considering plausible future risks.

Stress testing is a practical method to examine the impacts of both mean changes and changes in variability of rainfall. Portland, Oregon, for example, evaluated the peak intensity of precipitation on one scale and peak volume of precipitation on another scale (varying each 10% to 50% above baseline). Using this information, they could create scenarios to stress test their system and identify vulnerabilities.

The weather generator described above is another tool for stress testing a system. The weather generator is used to create plausible scenarios of future rain based on past observational data, simulating changes in both variability and changes in mean climate.

Risk Management

In 2018, ASCE published MOP 140, *Climate-Resilient Infrastructure: A Manual of Practice on Adaptive Design and Risk Management* to provide guidance for considering the uncertainties associated with a changing climate, although it is a step short of providing actual specifications typically embedded in an ASCE Code. The underlying approach in the MP140 manual of practice is based on probabilistic methods for quantitative risk analysis and provides a framework for analyzing low-regret, adaptive strategies to make a project more resilient to climate change.[18]

17 Casey Brown, Professor, University Of Massachusetts, Amherst

18 Bilal M. Ayyub, PhD, PE, Hon. M. ASME, Dist. M. ASCE Professor and Director, Center for Technology and Systems Management, Department of Civil and Environmental Engineering, University of Maryland

For risk management, there are two kinds of uncertainties to address: the known unknowns which can use reliability-based design or robust design practices; and the unknown unknowns inherent in planning for a changing environment where the uncertainty is unpredictable over time. In this latter case, ASCE recommends adopting an adaptive design with features that can be adapted over time without redoing it from scratch. This method brings together probabilities and consequences of various potential scenarios.

Policy Hurdles

But how do we translate to implementation? Once the risks and vulnerabilities have been evaluated and priorities are targeted, there are still three elements at play: upgrading codes and standards to provide guidance to engineers and planners; getting community buy-in including by the development community; and paying for infrastructure and addressing historical inequities.

Codes and Standards

State and local planning departments are taking steps to conduct various analyses, as described throughout this paper, but engineers and planners are seeking authoritative and sanctioned guidance to know what to design. Until and unless decisions are embedded into codes and standards, there is little mandate to require their use. This is a complex terrain involving federal government agencies, state agencies, local agencies, and standards setting bodies specific to different professions.[19]

For example, as we have seen, stormwater has both a water quality element and a drainage element which is not necessarily managed by the same departments. One lies largely in the realm of departments of the environment and the other often crosses into the realm of transportation departments. Typically, states take guidance from the Federal government (e.g., U.S. EPA and FHWA) and adopt requirements to meet or exceed those standards. In turn, counties and cities look to state standards to incorporate into local codes and ordinances. Standard setting bodies such as ASCE and others often develop the technical recommendations on how engineers should apply standards.

CASE STUDY:
Pittsburgh, PA

Recognizing the problem that severe storm events have increased 10-fold since 1950, and their 100-year-old system was not designed for such heavy events and with so much impervious surface, the City undertook a code update project. They adopted a progressive method to establish flow rates and volume control metrics that use rainfall data with climate change impacts factored in, rather than relying on historical data and outdated "typical year" scenarios. Specifically, the climate change policies require both volume controls for water quality, and rate controls to protect public health and safety. The new volume requirements for all regulated activities require controls for the 95th percentile rainfall using future climate change projections to 2100. Analyzing cost, they found a marginal cost difference in both pipe size and in acres treated, which was not considered to be unduly burdening for ensuring public health and safety.

Making changes throughout these interlocking realms will take time but, meanwhile, some communities faced with current impacts are forging ahead. Some states like Illinois have conducted their own analyses to update rainfall statistical data, and other states and localities are contracting with universities and consultants to evaluate modeled futures, such as Pittsburgh, PA and New York City; some counties and cities are amending ordinances to reduce vulnerabilities, such as Cambridge, MA, Pittsburgh, PA, and Virginia Beach, VA; and we are even finally beginning to see examples of infrastructure being built with future climate change in mind such as Boston and Cambridge, MA, Lake County, IL, and Anacortes, WA.

Some communities did their due diligence by conducting one or more sets of analyses to evaluate future changes in rainfall — and then rather than using the results directly in selecting code changes, they simply decided to upgrade to a different NOAA Atlas 14 return period. For example, the City of Madison, WI, after conducting several analyses, chose to simply move from 100-year to 200-year design storm standard; Ann

19 For example, see ASCE: https://www.asce.org/search#q=climate%20change&sort=relevancy

Arbor, MI, chose to change from its 100-year flood elevation standard to "the old 500-year standard."

In communities that are not ready to adopt new design standards, we learned how conducting analyses enabled them to simply figure out where their greatest vulnerabilities were in order to take various steps for improvements. Portland, OR, for example, tested a sensitivity analysis to evaluate the effects of different intensities and volumes of water, enabling them to identify where to target surgical upgrades to prevent overflows. Others are reexamining the combined effect of both gray and green infrastructure to manage pulses of water to reduce pressure on the system — without increasing pipe sizes. Using their sensitivity analysis, Portland was able to adopt green infrastructure methods in one neighborhood, avoiding the need to upsize the main trunk. Ann Arbor, MI redressed a serious flood risk by removing a railroad berm, thereby significantly dropping the floodplain elevation more than six feet.

Regardless of progress in these leading examples, all levels of government will eventually need to review and update their existing technical manuals, ordinances, codes, standards, regulations, and data sources to move the nation toward a climate resilient status.

Getting Buy-in

During this webinar series, we heard from communities who have been working for upwards of 15 years on getting buy-in to adopt changes. We learned from Illinois how initially there was resistance to upgrading the statistics in 1989. The development community later realized that this had been the right thing to do given the changing patterns of precipitation they experienced, and when it came time to again review and revise the data in 2020 there was strong support. Subsequently, Lake County, the seat of Chicago, IL, conducted 25 public meetings over 18 months resulting in requirements for all new regulated development, including larger detention basins, storm sewers, overland flow paths, wetland hydrology analyses, higher flood protection elevations for buildings, and more. In Welland, Ontario, near Niagara Falls, studies of rainfall patterns, system vulnerabilities, and potential design changes spanned 12 years, putting them in a position to now re-design infrastructure with strong public support. In Cleveland, OH, it took 15 years of outreach and system failures to convince the 62 communities in the sewer district's service area that stormwater management is an essential aspect of wastewater management — leading to a basin-scale strategy that included emphasis on flooding in disadvantaged communities. In Cambridge, MA, after conducting various analyses, the public supported revising codes for all new construction to protect from the projected year 2070 10-year storm and recover from the projected year 2070 100-year storm.

> *"It doesn't matter if you believe in climate change; your insurance company does,"*
>
> *Nick VinZant, senior research analyst for QuoteWizard, a subsidiary of Lending Tree, the online mortgage company.*

PITTSBURGH LESSONS LEARNED:

Pittsburgh's example provides some useful lessons Learned:

1. Stormwater management is both a land use issue and a climate change issue.
2. 70% of impervious areas are on private lands, not from rights of way, so managing runoff starts with codes and ordinances Ensuring codes are up to date and consider future climate change is key.
3. Requires watershed planning beyond the municipal boundary.
4. Must address the root cause, not just the symptoms.
5. Requires public and private investment.
6. Site specific. No "one-size-fits-all" stormwater solution.
7. Adaptive management approach. Programs should evolve based on lessons learned from past projects.
8. Solutions are not necessarily overly burdensome.

In other places changes took less time. Alarmed at what happened in Houston during Hurricane Harvey, in 2017, Boston, MA, created a dynamic H&H model to evaluate how to avoid such impacts and integrated it with a visualization to show the public how improvements would reduce risk. Virginia Beach, VA, involved the community in photographic documentation that ground-proofed the accuracy of their vulnerability assessment, helping to get buy-in from the public and decision makers for a comprehensive integrated watershed strategy that included revised codes.

Finally, there is the question of communicating with the public. Pittsburgh's success depended on having a process to understand what people are experiencing and to help the public and officials think differently about probabilities of future intense rainfall. In Cambridge, for example, planners used recent historic events to help bring context into the dialogue, conveying the concept that extreme events can happen not just once a year but can, in fact, be back-to-back (which underscores that the concept of a 100-year storm is not useful as a communication tool).

Funding and Equity

Climate stress is often felt as water stress and, combined with aging infrastructure, communities are in dire need of critical infrastructure upgrades. With the recent bipartisan infrastructure bill passed by Congress, massive amounts of funding will come available over the next five years; this provides an opportunity for communities to evaluate potential impacts of climate change to design systems to be as resilient as possible.

Economically disadvantaged communities are often affected first and worst by climate change and infrastructure failures. With the availability of new funding, the federal government working with state and local partners, can redress inequities using a variety of mechanisms. Under the Justice 40 initiative, 40% of benefits from federal investments in "covered programs", addressing topics such as climate change and clean water infrastructure, should be directed at disadvantaged communities. In addition, the Drinking Water State Revolving Fund and the Clean Water State Revolving Fund are USEPA's largest investment vehicles and make up a third of its entire budget — and half of the SRF funds will be given as 100% principal forgiveness loans, improving access to funds and technical assistance for even disadvantaged communities. But often such communities with the greatest need have the least technical and managerial capacity to access and use funds. To resolve this, USEPA plans to partner with states, philanthropies, universities, the labor community, and others to ensure expertise is available to provide assistance, and help build, operate, and maintain systems. In addition, some communities, such as New Orleans, LA are using social and economic data overlaid along with infrastructure vulnerability assessments to target investments to the most vulnerable communities. USEPA's EJScreen tool is also a widely referenced and useful tool for helping to identify areas needing investment.

Similarly the bipartisan infrastructure bill provides additional authorizations and funding for the U.S. EPA and U.S. Department of Transportation to address stormwater and resilience to climate change.[20] The Federal Lands Transportation Program requires entities carrying out projects to consider the use of native plants and designs that minimize runoff and heat generation; the DOT and EPA are required to retain the Transportation Resources Board to conduct a study on stormwater runoff and provide recommendations for states' departments of transportation; the FHWA is required to update two existing stormwater best management practices reports to reflect new information and advancements in the field; a new Healthy Streets grant program aims to help localities deploy cool and porous pavements and expand tree cover. to reduce impervious surfaces, storm water runoff, flood risks, and heat islands; ten regional Centers of Excellence for Resilience and Adaptation and a national Center are being created to advance research and development that improves the resilience of regions' surface transportation and related infrastructure.

20 Building a Better America: A Guidebook to the Bipartisan Infrastructure Law tor State, Local, Tribal, and Territorial Governments, and Other Partners, Feb. 1, 2022, at: https://www.whitehouse.gov/wp-content/uploads/2022/01/Building-A-Better-America_final.pdf. See also: Cities Advancing Climate Action: Leveraging Federal Funds for Local Impact A Resource Guide, C2ES, Jan. 2022, at: https://www.c2es.org/document/cities-advancing-climate-action-leveraging-federal-funds-for-local-impact-a-resource-guide/

Chapter 3:

PEER EXAMPLES

We can now document leading examples of communities taking action to build resilience to climate change. Several solid analytical tools are now available that communities can use according to their local capability and resources. It is possible to take interim steps to improve resilience as the nation continues to sort out all the changes needed to account for impacts of a changing climate.

- **Illinois:** Updating IDF Curves for State Regulations: Experiences from the State of Illinois ↗
- **Cambridge, MA:** Using Dynamic Models to Evaluate Climate-driven Vulnerabilities from Precipitation ↗
- **Welland, Ontario, Canada:** Climate Change Influenced IDF Curve Estimation for Managing Stormwater: A 12-year Journey ↗
- **Pittsburgh, PA:** Increasing Stormwater Resiliency Through Innovative Codes & Ordinances ↗
- **Additional Case Studies** from Previous Webinars ↗

Illinois

Updating IDF Curves for State Regulations: Experiences from the State of Illinois

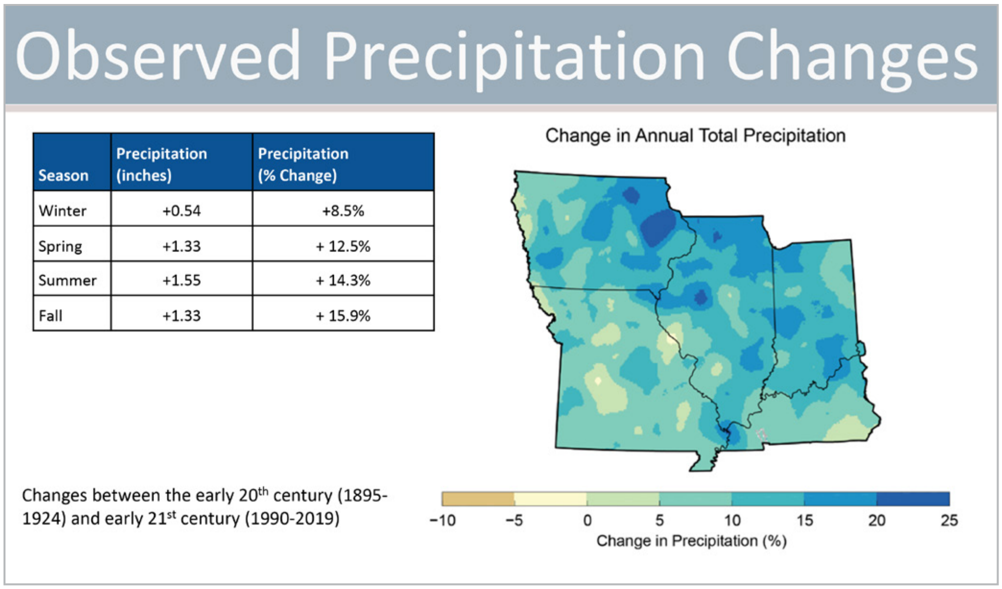
Jim Angel, Illinois State Water Survey

Over the years, Illinois was frustrated at the lack of updated precipitation statistics available to them so the State decided to conduct the analyses themselves. Bulletin 70 was produced in 1989 to replace TP-40, last provided by NOAA in 1961. Again, in 2020, Illinois felt the need to update their data to replace Atlas 14 Volume 2, last provided in 2004 based on the year 2000.

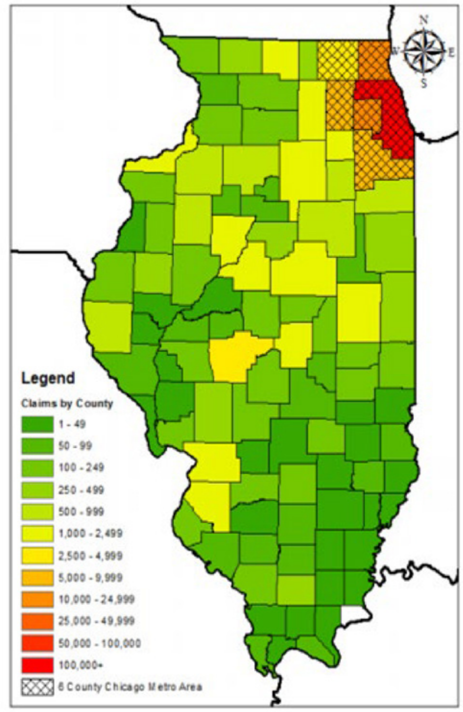
Their analysis revealed what they suspected: rainfall had substantially increased by 10%–15% from the 30-year period between 1895–1924 vs. 1990–2019. In the early part of the 20th century, it was rare to see extreme rainfall events greater than 2 inches, occurring perhaps once in 10 years. Starting in the 1950s, large rains became more common and 2014 saw a doubling in the number of 2-inch rain that a station could expect — one of the most pronounced impacts of climate change in their region. A report by the Illinois Department of Natural Resources on Urban Flooding indicated that the wetter climate, aging infrastructure, and runoff from urbanization was causing flooded basements, roadways, and businesses with $2.3B in losses from 2007 through 2018.

For the revised Bulletin 75 (2020), Illinois decided to use data collected during the 70 year period between 1948–2017 to better represent their current, wetter climate, and included three times as many rain gauge stations. They also chose to give more weight to the

- Wetter climate
- Aging infrastructure
- Urbanization - runoff



Source: Illinois State Water Survey



Source: Illinois State Water Survey

second half of the record (1983–2017) that showed a 5% increase over the first half. (Ancillary studies showed a potential 20% increase by the end of the century but this value is not yet used in the Illinois calculations.)

The result in the northern part of the state with 90% of Illinois' population and infrastructure was striking. The old TP-40 (1961) had indicated that the 100-yr., 24-hr. storm was 4 inches; Bulletin 70 (1989) showed 7.58 inches; and Bulletin 75 (2020) showed 8.57 inches. Under-designed infrastructure was causing the extra inches to become pure runoff.

Lake County took steps to redress their problems. They conducted 25 public meetings over 18 months to put into place the newly adopted Bulletin 75. As a result, all new regulated development requires larger detention basins, emergency spillways, storm sewers, overland flow paths, wetland hydrology analyses, higher flood protection elevations for buildings, and public health requirements.

Given that it could be several years before NOAA issues a nationwide analysis with updated methodology to reflect nonstationarity under climate change, Illinois continues to have conversations about how to plan for the future. It is not clear what the best solution is — but they are working on it.

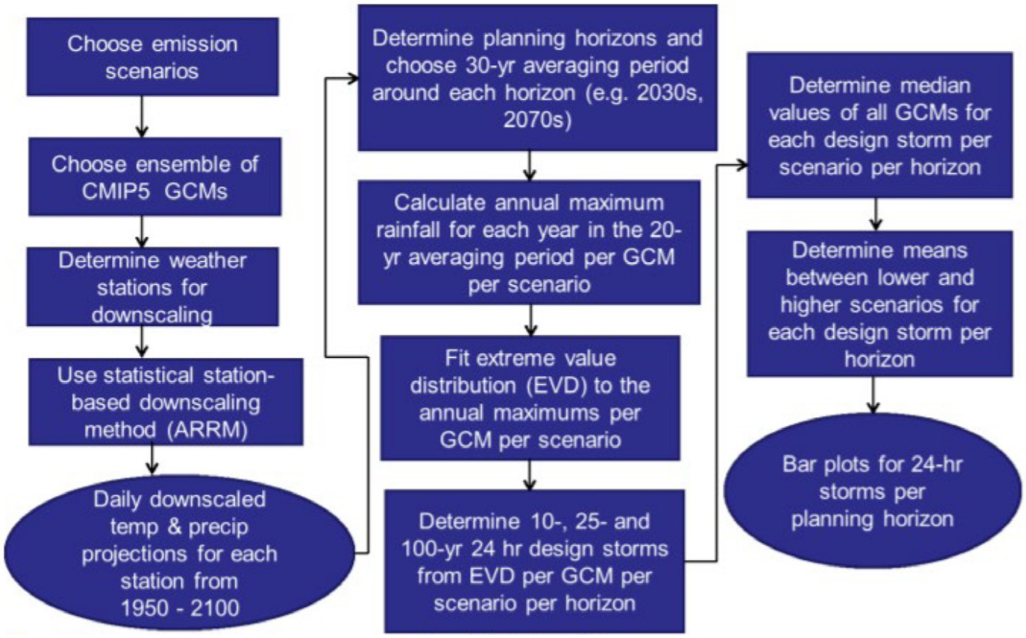
Cambridge, MA

Using Dynamic Models to Evaluate Climate-driven Vulnerabilities from Precipitation

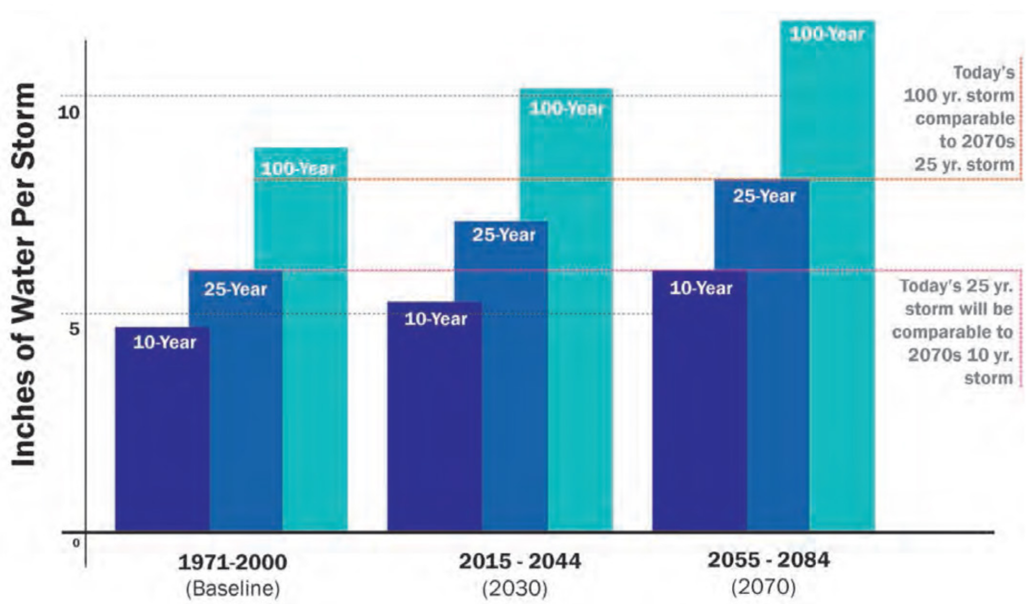
John Bolduc, City of Cambridge, and Indrani Ghosh, PhD, Weston & Sampson.

Resilient Cambridge

The City of Cambridge, MA, first began working on adaptation in 2010 when they realized that most of their flood risk was related to urban street flooding *outside of the FEMA flood zone*, and under the changing climate they expected it to get worse. Cambridge began with a climate change vulnerability assessment for 2030 and 2070 by conducting a stress test to understand what would happen if they were to see more water and higher temperatures. The results were striking: they realized that it was not possible to store and convey their way out of flood risk, but they could reduce the risk. They would have to adapt to some flooding.



Source: City of Cambridge, MA



100 yr. will be 25 yr., 25 yr. will be 10 yr. storm. Source: City of Cambridge, MA

The City then undertook a full vulnerability assessment that formed the baseline foundation for a roadmap to adaptation. In the end, the City developed 34 strategies organized around 1) Neighborhoods, 2) Better Buildings, 3) Stronger Infrastructure, and 4) Greener Cities. They produced a main document, 6 technical memos, a handbook with details of the 34 strategies, a summary report, 4 story maps, and a flood viewer tool providing flood extent and elevation data at the parcel level.

To get there the City contracted with a contractor in 2013 to conduct a vulnerability assessment that incorporated projections based on climate scientist Dr. Katherine Hayhoe's statistical downscaling. She used RCP4.5 and 8.5 (high and moderate emissions pathways) and chose an ensemble of 12 models to come up with daily rainfall projections.

Traditional indicators for extreme precipitation (the number of days per year with more than 2 inches of rain and the wettest 5-day period) help to understand

Credit: City of Cambridge, MA

trends but are not useful for designing infrastructure. Instead, the City's contractor used Dr. Hayhoe's projections to adjust for the extreme value distribution based on the two GCM scenarios for the 30-year periods with midpoints in 2030 and 2080 to come up with the statistics needed for designing infrastructure: from the 2-year storm to the 100-year. They found that today's 25-year rainfall would become the 10-year rainfall by 2070, and today's 100-year rain would be comparable to the 25-year rain.

Next, they developed a dynamic integrated flood model linking precipitation-driven surface water, riverine water, Cambridge's piped infrastructure, dam operations, and sea level rise/storm surge in one comprehensive flood model to understand the interplay of extreme weather with the system. They could then use the future rainfall projections to understand their future flood risk. The interactive Cambridge Flood Viewer web application is publicly available so that residents can simply type in their address to find the results of different scenarios for their property.[21]

The results enable Cambridge to develop citywide flood maps to compare to the FEMA flood zones. While the current NOAA Atlas 14 data indicates that Cambridge's 100-year, 24-hour storm is 8.9 inches, the City found that in 2030 it is likely to be more than 10 inches and in 2070 almost 12 inches. These values are similar to the current 500-year storm.

The newly developed flood maps are now being used in city ordinances for all new development with the goal of protecting to the 2070 10-year storm but recovering from the 2070 100-year storm. Requirements include infrastructure improvements, siting green infrastructure, and maximizing the co-benefits of reducing the urban heat island and protecting water quality. Examples of new requirements include:

- Closer Neighborhoods — establish support hubs, provide healthcare continuity and access, support renter preparedness
- Better Buildings — use flood resilient materials, build exterior flood walls, install backwater valves, elevate/relocate utilities
- Stronger Infrastructure — green and gray infrastructure improvements

21 Cambridge Flood Viewer, https://www.cambridgema.gov/Services/floodmap

"Fantastic resources and information ... It is answering questions I dealt with on the municipal side for a long time, and new questions I have in water treatment/distribution. I know my former colleagues ... are on the call and feel the same way."

- Greener Cities — reduce urban heat island effects (mitigate by 20 F and decrease by 15%) with effective implementation of increased trees, green infrastructure, and white roofs.)

The city is now using their analyses to inform infrastructure decisions. Details are available about several projects: Port Infrastructure project, MIT statistics center stormwater basin, Longfellow Park infiltration, Sidney Street green roof, and Finch Cambridge affordable housing.

The next steps include a new climate resilience zoning task force that is codifying the new 2070 flood standard and adding a cool factor rating system (performance-driven standards which contribute to public realm cooling, the mitigation of heat island effects, and a greener Cambridge. To share their experience and collaborate on a broader watershed scale, Cambridge is engaged with three regional collaborations: the Metro Mayors Climate Task Force involving more than 15 communities, the Resilient Mystic Collaborative with 21 watershed communities, and the Charles River Climate Compact with 23 communities.

Welland, Ontario, Canada

Climate Change Influenced IDF Curve Estimation for Managing Stormwater: A 12-year Journey

Peter Nimmrichter, M.Eng., P.Eng., IRP, Wood PLC

The Canadian Public Infrastructure Engineering Vulnerability Committee (PIEVC)[22] was created in August 2005 to conduct an engineering assessment of the vulnerability of Canada's public infrastructure to the impacts of climate change. It's 2008 report[23] found that:

5. Some infrastructure components have high engineering vulnerability to climate change.
6. Improved tools are required to guide professional judgment.
7. Infrastructure data gaps are an engineering vulnerability.
8. Improvement is needed for climate data and climate change projections used for engineering vulnerability assessment and design of infrastructure.
9. Improvements are needed in design approaches.
10. Climate change is one factor that diminishes resiliency.
11. Engineering vulnerability assessment requires multi-disciplinary teams.

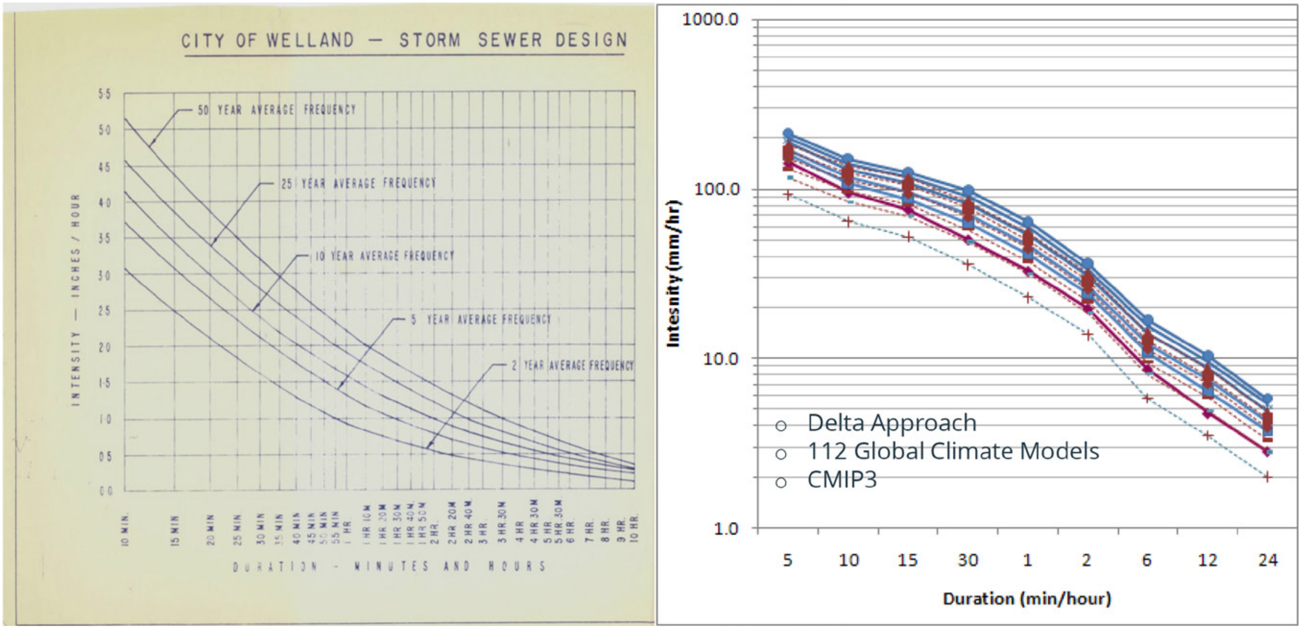
After this report came out, the City of Welland, Ontario, a city of 50,000 residents on the Niagara peninsula just 20 miles west of Buffalo, New York, realized that their storm sewer system was based on statistics dating back to 1963 so in 2009 the City decided to update their IDF statistics.

Welland analysts then used the PIEVC 5-step protocol to conduct a climate vulnerability assessment of their stormwater, sanitary sewer, and wastewater

22 Between August 2005 and June 2012 the committee's activities were co-funded by Natural Resources Canada (NRCan) and Engineers Canada. As of March, 2020, operations of the PIEVC Protocol and PIEVC Program have been assumed by the PIEVC Program Partnership, consisting of the Institute for Catastrophic Loss Reduction (ICLR), the Climate Risk Institute (CRI) and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

23 Adapting to Climate Change Canada's First National Engineering Vulnerability Assessment of Public Infrastructure April 2008. Engineers Canada, Canadian Council of Professional Engineers. https://pievc.ca/wp-content/uploads/2020/12/adapting_to_climate_change_report_final.pdf

1963 **2020 & 2050**



Intensity, Duration, Frequency Curves updated in 2009 and projected to 2050.
City of Welland, Ontario, Canada. Source: Wood, PLC.

systems. Welland analysts used a delta change approach based on CMIP3 to look out to 2050, a modest $20,000 effort. The results led the City to develop a climate change adaptation plan with 44 recommendations — the first of which were to evaluate the implications of using their revised IDF curves under future climate projections as well as the implications of using upgraded design criteria for their storm sewer design.

It wasn't until 2014 that Welland was able to conduct those assessments.[24] The city examined the influence of the various IDF rainfall relationships on the design of stormwater management end-of-pipe and conveyance systems; evaluated the implications of changing the existing 2-year design criterion for storm sewers to a 5-, 10- or 25-year return period to account for future rainfall; and assessed the change in construction costs. The findings were dramatic. They found that by 2050 they would need to increase the system's maximum volume by 89%, and that *updating pipes by 1 increment would cover almost all future rainfall at an incremental cost.*

Their analysis led them to conclude that:

- Adaptation options vary for different types of infrastructure
- Adaptation options vary by geography
- Adaptation need not be complicated
- Timing of critical decision-making will vary depending on vulnerability and opportunity
- The incremental cost associated with new development is not excessive

The Welland journey continued in 2017 when the City conducted a forensic review using dynamic modeling to investigate how the stormwater management system would perform under future climate scenarios. The study revealed existing and potential future problems including uncontrolled spills during 25-year storms and overflows from 10-year storms. They realized that climate change was driving increased system surcharging and at-surface flooding.

24 Wood, PLC, has recently developed ResilienceLens, an interactive web-based project screening tool for dynamic precipitation frequency analysis on climate model projections. It includes pre-processed precipitation data for 32 climate models to provide fast queries and quick results. Based on Transportation Research Board methodology, the user interface helps to select locations, time periods, climate models, and distribution type, and compares projections against NOAA Atlas-14. It then produces visualizations for insight into climate model results. The TRB report, Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure, can be found here: http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4046

But while they realized that existing issues will just get worse, it wasn't so easy to address the problems. They were facing challenges including maintaining the design basis over a long development period; the need for room to expand facilities; the challenge of gaining acceptance for resilience initiatives; and the requirements already in existing permits.

Continuing to work on the challenge, in 2019 Welland assessed the impact of future IDF rainfall on 11 stormwater management facilities to integrate adaptive capacity into pond rehabilitation. They decided that they needed to alter outflow controls to maintain existing outflow volumes, and that they would need to integrate adaptive capacity upgrades into their pond rehabilitation program.

Starting in 2021, Welland has been conducting stormwater management facility cleanouts and pond retrofits of ponds while working to update municipal guidelines. Despite Welland's decade-long journey, the steps involved were not overly onerous for a small city like Welland, with its population of 60,000. Their experience demonstrates how to understand the implications of changes in precipitation for the performance of installed infrastructure, and the importance of finding solutions to the institutional, financial, and public buy-in challenges.

"Would like to see more of these technical webinars and what resources and technical equipment NOAA has and is using to collect data (also accuracy) Thank you."

Pittsburgh, PA

Increasing Stormwater Resiliency Through Innovative Codes & Ordinances

James Stitt, Manager of Sustainability, Pittsburgh Water and Sewer Authority; and Tom Batroney, PE, CFM, Technical Director, Pittsburgh Office, AKRF.

Source: Pittsburgh Water and Sewer Authority

Pittsburgh, PA's stormwater system is more than 100 years old. Approximately 25% of the old pipes are still in use — that is 1,200 miles of sewers that are still in use today that were in the ground by 1908. And, like most cities in the region with old systems, maintenance had been deferred taking a "fix as fail" firehouse approach. Meanwhile, Pittsburgh has drastically changed in the last 120 years, as it has grown vertically and is more spread out as it reaches further into the hills with more impervious area.

Using available rainfall data from NOAA and others, Pittsburgh's planners can see the trend that "severe events" are significantly increasing over time. In fact, since 1950, severe storm events in Allegheny County have increased 10-fold. Needless to say, the old system is not designed for such heavy events and with so much impervious surface.

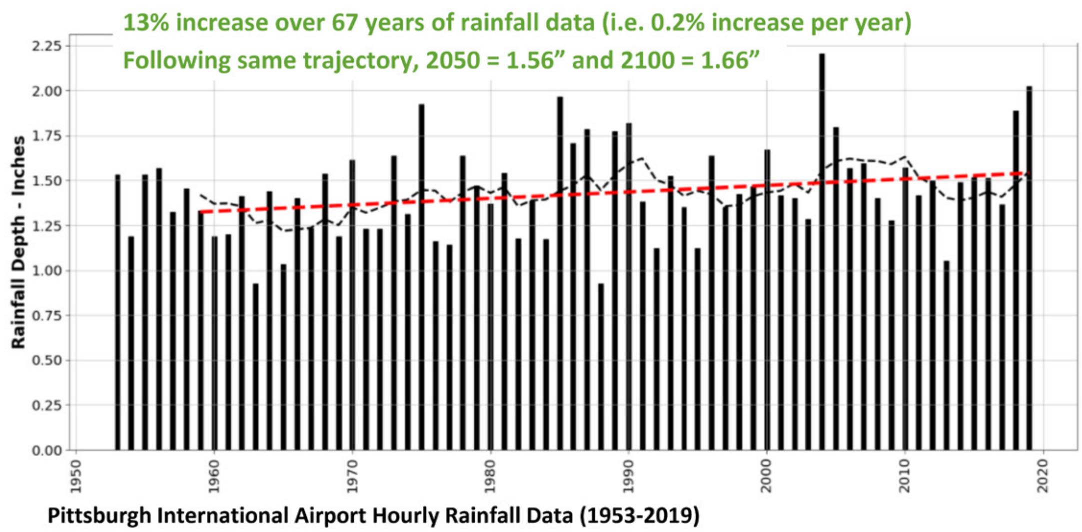
Future Design Storm Estimates

Return Period (Yr)	Current Code Requirements	CMU/RAND Climate Change Study	Percent Difference between Existing and Future Climate Return Period Values			
	NOAA Atlas 14 (inches of rainfall)	2100 Average Future* (inches of rainfall)	Pittsburgh	VA Beach	Auckland, NZ	Vancouver, BC
2	2.3	2.5	8%	20%	9%	21%
5	2.9	3.3	12%	20%	11%	19%
10	3.3	3.9	15%	20%	13%	22%
25	3.9	4.8	19%	20%	15%	21%
50	4.4	5.6	21%	20%	17%	21%
100	4.9	6.4	23%	20%	17%	20%

*Values taken from Table C.4 *Managing Heavy Rainfall with Green Infrastructure* (RAND 2020)

Source: Pittsburgh Water and Sewer Authority

Future 95th Percentile Rain Event

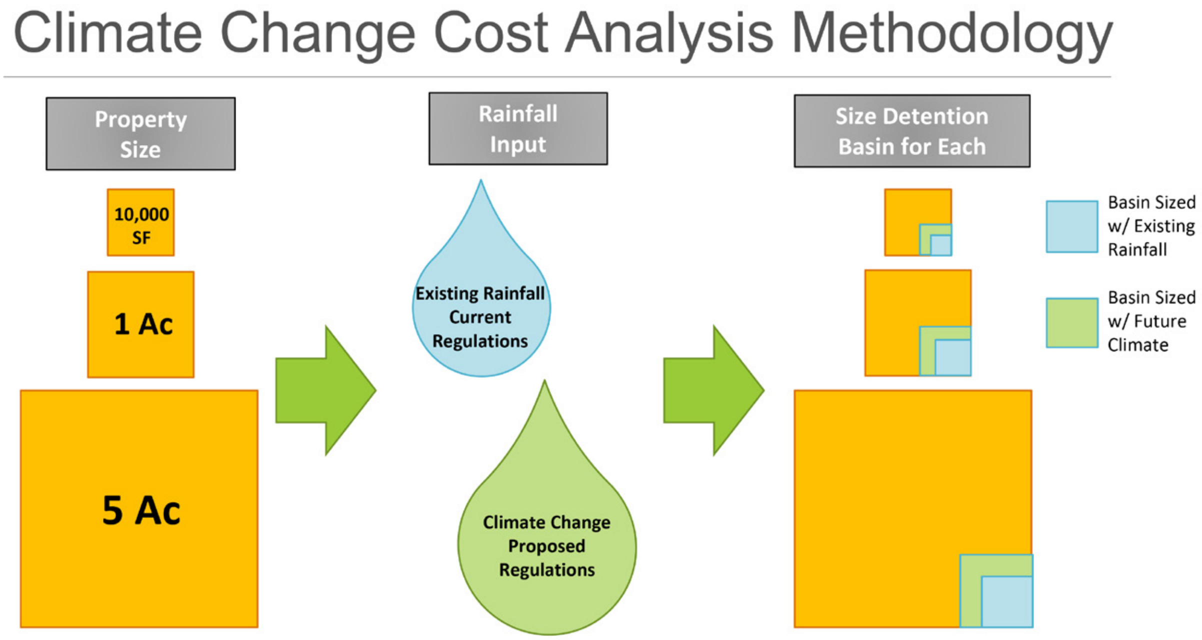


Source: Pittsburgh Water and Sewer Authority

In the past, Pittsburgh lacked a unified stormwater strategy. The stormwater codes were dispersed throughout the City’s various Titles and Ordinances, resulting from an ad hoc assemblage over many years. The inconsistency and contradictions between codes made it difficult to comprehend for both the regulated community as well as the City’s regulators.

Recognizing the problem, the City undertook a code update project. They sought out the assistance of a contractor to help revise and update the stormwater codes. Pittsburgh consolidated all the related content under a new *Title 13 — Stormwater* (passed in October 2021 and effective March 2022) and eliminated conflicts, streamline the permitting processes; new technical resources were developed to aid implementation.

Essential to the project was adoption of a progressive method to establish the flow rate and volume control metrics that uses rainfall data with climate change impacts factored in, rather than relying on historical data and outdated “typical year” scenarios.



Source: Pittsburgh Water and Sewer Authority

Specifically, the climate change policies require both volume controls for water quality, and rate controls to protect public health and safety.

The new volume requirements for all regulated activities require controls for the 95th percentile rainfall using future climate change projections to 2100. The city had seen a 13% increase in volume over 67 years of rainfall data (1953–2019). Following the same trajectory, designing for 2050 would require a design for 1.56 inch, and 2100 would require a design to 1.66 inch — not a huge ask when it comes to sizing and cost.

Rate controls also require use of 2100 climate projections. Peak flow rate for post development runoff is not allowed to exceed peak flow rate from the pre-development based on the existing NOAA Atlas 14 values for the 1- through 100-year, 24 hour rainfall events. To ground truth these values, the City looked to a study by Carnegie Mellon and Rand, *Managing Heavy Rainfall with Green Infrastructure* (RAND 2020), that compared the 2-100 yr. return period for Atlas 14 vs. 2100 for Pittsburgh, and compared values generated by others for peer cities using various methods They all resulted in broadly similar values.

Pittsburgh also examined how the flow rate policy would affect residents in known flood prone areas. Planners ranked the City's watersheds using a flood susceptibility score, evaluated flooding complaints, and modeled specific watersheds using SWMM and the existing hydraulic capacity model. They then evaluated the cost to reduce the post-development 10-year, 24-hour peak flow with climate change over the pre-development 2-year, 24-hour peak flow with existing rainfall. Again, they found a marginal cost difference, on the order of some tens of thousands per acre for both a small site and a large site, considered not unduly burdening for ensuring public health and safety.

Pittsburgh's example provides some useful lessons Learned:

1. Stormwater management is both a land use issue and a climate change issue.
2. 70% of impervious areas are on private lands, not from rights of way, so managing runoff starts with codes and ordinances. Ensuring codes are up to date and considered future climate change is key.
3. Requires watershed planning beyond the municipal boundary.
4. Must address the root cause, not just the symptoms.
5. Requires public and private investment.
6. Site specific. No "one-size-fits-all" stormwater solution.
7. Adaptive management approach. Programs should evolve based on lessons learned from past projects.
8. Solutions are not necessarily overly burdensome.

Additional Case Studies from Previous Webinars

- **Boston, MA:** What if it happened here?
  https://toolkit.climate.gov/case-studies/what-if-it-happened-here-boston-takes-lesson-houston%E2%80%99s-hurricane-harvey

- **Portland, OR:** Throw Away Your Crystal Ball: A Stress Testing Approach to Infrastructure Planning Under Climate Change Uncertainty
  https://toolkit.climate.gov/case-studies/throw-away-your-crystal-ball-stress-testing-approach-infrastructure-planning-under

- **Virginia Beach, VA:** Virginia Beach Becomes Sea Level Wise.
  https://toolkit.climate.gov/case-studies/virginia-beach-becomes-sea-level-wise

- **Pittsburgh, PA:** Pittsburgh Unifies Its Approach to Stormwater Management.
  https://toolkit.climate.gov/case-studies/pittsburgh-unifies-its-approach-updating-stormwater-management

- **Two Harbors, MN:** Investments in Green Infrastructure Pay Off.
  https://toolkit.climate.gov/case-studies/two-harbors-investments-green-infrastructure-pay

APPENDICES

Appendix I: References and Resources

NOTE: Webinar recordings and slides found at: https://cpo.noaa.gov/Meet-the-Divisions/Climate-and-Societal-Interactions/Water-Resources/Water-Utility-Study

Session 1 | Focus on Science

SEPTEMBER 14, 2021 2:00 - 3:30 EDT

Objective: Understand the state of the science on precipitation prediction and climate modeling

Precipitation Prediction - A Probabilistic Endeavor - David Novak (NOAA National Weather Service)

- Weather Prediction Center. https://www.wpc.ncep.noaa.gov, (retrieved November 12, 2021).

Precipitation Prediction - Research Needs - Jin Huang (NOAA CPO)

- NOAA-DOE Precipitation Processes and Predictability Workshop, 15 October 2020, https://cpo.noaa.gov/News/News-Article/ArtMID/6226/ArticleID/2030/NOAA-DOE-Precipitation-Processes-and-Predictability-Workshop (retrieved November 12, 2021).

Global Climate Models: CMIP6 - what we know and don't know on projecting future precipitation - Kenneth Kunkel (North Carolina State University/NOAA Cooperative Institute for Satellite Earth System Studies)

- U.S. Climate Resilience Toolkit. U.S. Climate Resilience Toolkit. https://toolkit.climate.gov/tool/climate-explorer-0 (retrieved November 12, 2021).

Session 2 | From Science to Application: Climate Science, Hydrology, and Planning – Part 1

SEPTEMBER 21, 2:00 - 3:30 PM EDT

Objective: Learn about: results of studies evaluating local and regional trends in extreme events, different approaches for evaluating future precipitation, an analysis of current state stormwater infrastructure standards, and a method being considered by the American Society of Civil Engineers (ASCE) for a Climate-Resilient Infrastructure standard.

Climate Change and Rainfall IDF Statistics - Daniel Wright (University of Wisconsin-Madison)

The Wisconsin Rainfall Project. https://her.cee.wisc.edu/the-wisconsin-rainfall-project/ (retrieved November 12, 2021).

- Wisconsin Initiative on Climate Change, Trends and Projections. https://wicci.wisc.edu/wisconsin-climate-trends-and-projections/; https://her.cee.wisc.edu/rainyday-rainfall-for-modern-flood-hazard-assessment/ (retrieved November 12, 2021)
- RainyDay Software, Daniel B. Wright, GitHUB. https://github.com/danielbwright/RainyDay2 (retrieved November 12, 2021)
- Alexander, G.N.. (1963). Using the Probability of Storm Transposition for Estimating the Frequency of Rare Floods, Journal of Hydrology, Volume 1, Issue 1, March 1963, Pages 46-57. https://www.sciencedirect.com/science/article/abs/pii/0022169463900325.
- Lopez-Cantu, T. and C. Samaras. (2018). "Temporal and spatial evaluation of stormwater engineering standards reveals risks and priorities across the United States." Environ. Res. Lett. 13 074006. DOI:10.1088/1748-9326/aac696. https://iopscience.iop.org/article/10.1088/1748-9326/aac696.
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- Wright, D. B., Bosma, C. D., & LopezCantu, T. (2019). U.S. hydrologic design standards insufficient due to large increases in frequency of rainfall extremes. Geophysical Research Letters, 46, 8144–8153. https://doi.org/10.1029/2019GL083235.
- Wright, D.B., C. Samaras, and T. Lopez-Cantu. (2021). "Resilience to Extreme Rainfall Starts with Science." *Bulletin of the American Meteorological Society.* Page(s): E808–E813. https://doi.org/10.1175/BAMS-D-20-0267.1.

- Wright, D.B., G. Yu, and J.F. England. Six Decades of Rainfall and Flood Frequency Analysis Using Stochastic Storm Transposition: Review, Progress, and Prospects. Journal of Hydrology, 2020. https://www.researchgate.net/publication/339846480_Six_Decades_of_Rainfall_and_Flood_Frequency_Analysis_Using_Stochastic_Storm_Transposition_Review_Progress_and_Prospects.
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- Wright, Danial B., et. al. Estimating the frequency of extreme rainfall using weather radar and stochastic storm transposition, Journal of Hydrology, 2013. https://her.cee.wisc.edu/papers/SST_jhydrology.pdf.
- Wright, D.B., R. Mantilla, and C.D. Peters-Lidard. A remote sensing-based tool for assessing rainfall-driven hazards, Environmental Modeling & Software, 2017. https://www.sciencedirect.com/science/article/abs/pii/S1364815216311549.
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- Zhou, Zhengzheng, et. al. (2021). The impact of spatiotemporal structure of rainfall on flood frequency over a small urban watershed: an approach coupling stochastic storm transposition and hydrologic modeling. 10.5194/hess-2021-161. https://hess.copernicus.org/articles/25/4701/2021/hess-25-4701-2021-relations.html.

Climate-Resilient Infrastructure: Adaptive Design and Risk Management - Bilal M. Ayyub (University of Maryland and American Society of Civil Engineers)

- ASCE climate change topic: https://www.asce.org/search#q=climate%20change&sort=relevancy (retrieved Nov. 12, 2021
- Ayyub, B. M., and Alice Hill. Climate-Resilient Infrastructure: Engineering and Policy Perspectives, *The Bridge*. National Academy of Engineering, 2019. Volume 49 Issue 2, https://www.nae.edu/212185/ClimateResilient-Infrastructure-Engineering-and-Policy-Perspectives

- Climate-Resilient Infrastructure: A Manual of Practice on Adaptive Design and Risk Management. Edited by B.M. Ayyub, ASCE Manual of Practice 140, American Society of Civil Engineers, Reston, VA. 2018. https://ascelibrary.org/doi/pdf/10.1061/9780784415191.fm.
- Extreme Precipitation Analysis and Prediction for a Changing Climate. Huiling Hu, and Bilal M. Ayyub. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, Vol. 4, Issue 3 (September 2018). https://ascelibrary.org/doi/abs/10.1061/AJRUA6.0000980.
- Hazard-Resilient Infrastructure: Analysis and Design. Edited by Bilal M. Ayyub , Ph.D., P.E.; ASCE MOP 144, American Society of Civil Engineers, Reston, VA. 2021. https://ascelibrary.org/doi/book/10.1061/9780784415757
- Hill, A. C., et. al. "Ready for Tomorrow: Seven Strategies for Climate Resilient Infrastructure." *A Hoover Institution Essay*, Stanford University, The Johnson Center, April 19, 2019, https://www.hoover.org/research/ready-tomorrow-seven-strategies-climate-resilient-infrastructure.
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- *Minimum Design Loads for Buildings and Other Structures*, Standard ASCE 7. https://ascelibrary.org/doi/book/10.1061/asce7

Utility Interrogatory and Utility Perspectives - Charles Bodnar (Public Works Stormwater Engineering Center, VA Beach, VA)

- Analysis of Historical and Future Heavy Precipitation, City of Virginia Beach, Virginia, 2018. https://www.vbgov.com/government/departments/public-works/comp-sea-level-rise/Documents/anaylsis-hist-and-future-hvy-precip-4-2-18.pdf (retrieved Nov. 12, 2021).

Session 3 | From Science to Application: Climate Science, Hydrology, and Planning – Part 2

SEPTEMBER 28, 2:00 - 4:00 EDT

Objective: Learn about some of the ways researchers are helping communities consider climate change in local planning. Participants will gain insights into approaches for evaluating climate change impacts on hydrology for planning.

Integrating Climate Model Downscaling and IDFs - Extreme Precipitation Statistics Adjusted for Changing Climate - Art DeGaetano (Cornell University and the Northeast Regional Climate Center)

- Extreme Precipitation in NY and NE (Precip.net). http://precip.eas.cornell.edu/ (retrieved November 12, 2021).

- Projected Intensity-Duration-Frequency Curve Data for the Chesapeake Bay Watershed and Virginia. Mid-Atlantic RISA. https://midatlantic-idf.rcc-acis.org/ (retrieved November 12, 2021).
- Recent Extreme Precipitation Changes in the Northeast U.S. https://precipchange.nrcc.cornell.edu (retrieved November 12, 2021).

Projected Changes Precipitation IDF Curves for California - Amir AghaKouchak (University of California-Irvine)

- AghaKouchak, Amir, et. al. (University of California, Irvine). 2018. *Projected changes in California's precipitation intensity- duration-frequency curves.* California's Fourth Climate Change Assessment, California Energy Commission. Publication Number: CCCA4-CEC-2018-005. https://www.energy.ca.gov/sites/default/files/2019-11/CCCA4-CEC-2018-005_ADA.pdf.
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From Climate Vulnerability to Adaptation - Climate Informed Water Planning - Casey Brown (University of Massachusetts-Amherst)

- *Climate Risk Informed Decision Analysis (CRIDA) - Collaborative Water Resources Planning for an Uncertain Future.* 2018. UNESCO International Centre for Integrated Water Resources Management; Mendoza, Guillermo; Jeuken, Ad; Matthews, John; Stakhiv, Eugene; Kucharski, John; Gilroy, Kristin. https://en.unesco.org/crida.
- Ray, Patrick A., Casey M. Brown. 2015. *Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework.* Washington, DC: World Bank. http://hdl.handle.net/10986/22544

Utility Interrogatory and Utility Perspectives - Azya Jackson (Los Angeles Sanitation and Environment)

- One Water LA — Volume 6, *Climate Risk & Resilience Assessment for WW and SW Infrastructure*, https://bit.ly/3LwYe5B

Session 4 | What’s on the Horizon for Science and Application of Climate Change Information for Water Infrastructure Managers?

OCTOBER 5, 1:30 - 3:00 EDT

Objective: An interdisciplinary conversation among thought leaders to provide participants an idea of what is on the horizon for helping communities build resilience of water management infrastructure and how we can move forward as a nation.

NOAA’s Precipitation Prediction Grand Challenge - Wayne Higgins (NOAA Oceanic and Atmospheric Research/Climate Program Office)

- Balmaseda M, et. al. 2020. “NOAA-DOE Precipitation Processes and Predictability Workshop.” U.S. Department of Energy and U.S. Department of Commerce NOAA; DOE/SC-0203; NOAA Technical Report OAR CPO-9 https://climatemodeling.science.energy.gov/news/noaa-doe-precipitation-processes-and-predictability-workshop-report-now-available
- NOAA-DOE Precipitation Processes and Predictability Workshop, 15 October 2020, https://cpo.noaa.gov/News/News-Article/ArtMID/6226/ArticleID/2030/NOAA-DOE-Precipitation-Processes-and-Predictability-Workshop (retrieved November 12, 2021).
- National Water Center, https://water.noaa.gov/about/nwc (retrieved Nov. 12, 2021)

Precipitation Frequency Estimation - Atlas 14 and Beyond - Mark Glaudemans (NOAA Office of Water Prediction)

- *Analysis of Impact of Non-stationary Climate on NOAA Atlas 14 Estimates: Assessment Report*, National Weather Service Office of Water Prediction, Jan. 31, 2022. https://hdsc.nws.noaa.gov/hdsc/files25/NA14_Assessment_report_202201v1.pdf.
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- *FEMA Offers More Equitable Flood Insurance Rates Beginning Oct. 1,* https://www.fema.gov/press-release/20210924/fema-offers-more-equitable-flood-insurance-rates-beginning-oct-1 (accessed Nov. 12, 2021)
- FLOODS Act, https://www.congress.gov/bill/117th-congress/house-bill/1438/text
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Meeting the Moment: Equity, Climate, and Water Infrastructure - Zach Schafer (USEPA Office of Water)

- USEPA. 2021. Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. U.S. Environmental Protection Agency, EPA 430-R-21-003. www.epa.gov/cira/social-vulnerability-report.
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- USEPA Creating Resilient Water Utilities, https://www.epa.gov/crwu#:~:text=EPA's%20CRWU%20initiative%20provides%20drinking,increase%20resilience%20to%20climate%20change (retrieved Nov. 12, 2021).
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Use of Precipitation Information with Federal Highways - Daniel Sharar-Salgado (US Department of Transportation, Federal Highways Administration)

- Federal Highways Administration, (2016). *Highways in the River Environment - Floodplains, Extreme Events, Risk, and Resilience* (Hydraulic Engineering Circular No. 17). U.S. Department of Transportation, Washington, D.C. https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf
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Session 5 | Peer Examples: Evaluating Changing Precipitation Trends for Managing Water Infrastructure

OCTOBER 12, 1:30 - 3:30 EDT

Objective: Provide examples of how some communities are moving forward, using future precipitation considerations for local decision making

Updating IDF Curves for State Regulations: Experiences from the State of Illinois - Jim Angel (Illinois State Water Survey, emeritus)

- Angel, J. R., et., al. 2020. Precipitation Frequency Study for Illinois. Illinois State Water Survey Bulletin 75, Champaign, IL. http://hdl.handle.net/2142/106653.
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- Winters, B. A., et. al. 2015. Report for the Urban Flooding Awareness Act. Springfield, IL: Illinois Department of Natural Resources. http://hdl.handle.net/2142/78150.

Using Dynamic Models to Evaluate Climate-driven Vulnerabilities from Precipitation - John Bolduc (Cambridge, MA) and Indrani Ghosh (Weston & Sampson)

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- City Cambridge, MA [n.d.] Understanding Flood Risks & Protecting Your Property https://www.cambridgema.gov/Services/floodmap
- Regional Climate Collaborations:
  - Metro Mayors Climate Task Force, The 15 communities of the Metro Mayors Climate Task Force work together and with federal and state agencies to address vulnerabilities in Metro Boston's communities and shared infrastructure. https://www.mapc.org/our-work/expertise/climate/mmc/
  - Resilient Mystic Collaborative, The Resilient Mystic Collaborative is a partnership among neighboring communities in Greater Boston's Mystic River Watershed working to protect our people and places from climate-intensified risks, https://resilient.mysticriver.org/ and Managing Regional Flooding
  - Upper Mystic Stormwater Work Group https://resilient.mysticriver.org/upper-mystic-stormwater

Climate Change Influenced IDF Curve Estimation for Managing Stormwater: A 15-year Journey - Welland, Ontario, Canada - Peter Nimmrichter (Wood PLC)

- AMEC Environment & Infrastructure (February 2012). City of Welland Stormwater and Wastewater Infrastructure Assessment — Technical Report. [Report No. TP111002-001] https://www.welland.ca/Eng/pdfs/TP111002WellandVol001Final.pdf.
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Centralizing Management of Municipal Stormwater and Implementing Updated Depth-Duration-Frequency Curves - James Stitt (Pittsburgh Water and Sewer Authority) and Tom Batroney, Licensed Professional Engineer (AKRF)

- Cook, L.M., S. McGinnis, ande C. Samaras. The effect of modeling choices on updating intensity-duration-frequency curves and stormwater infrastructure designs for climate change. *Climatic Change* **159**, 289–308 (2020). https://doi.org/10.1007/s10584-019-02649-6
- Fischbach, Jordan R., et. al. Managing Heavy Rainfall with Green Infrastructure: An Evaluation in Pittsburgh's Negley Run Watershed. Santa Monica, CA: RAND Corporation, 2020. https://www.rand.org/pubs/research_reports/RRA564-1.html. Also available in print form.

USEPA Creating Resilient Water Utilities: Experience Working with Communities - Curt Baronowski (US Environmental Protection Agency)

- US EPA. *Creating Resilient Water Utilities* (CRWU). https://www.epa.gov/crwu. (retrieved November 12, 2021).

Scientist Interrogatory - Debra Knopman (RAND Corporation and Mid-Atlantic Regional Integrated Sciences and Assessment (MARISA))

- Mid-Atlantic RISA. Projected Intensity-Duration-Frequency Curve Data Tool for the Chesapeake Bay Watershed and Virginia. https://midatlantic-idf.rcc-acis.org/ (retrieved November 12, 2021).
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Appendix II: Webinar Participation Profile

Registrants: 2,051	**Total Views:** 3,193	**Unique Viewers:** 1,510

Demographics of Series Participation (poll respondents)

What is your organizational affiliation type?	Count
Local government (population less than 100,000)	90
Local government (population 100,000 - 500,000	48
Local government (population 500,000 - 1 million)	34
Local government (population greater than 1 million	46
State government	105
Federal government	90
Investor-owned utility services company	2
Private Consultant - Engineering Services	93
Private Consultant - Environmental Services	29
Private Consultant - Policy	6
Academia	80
NGO	31
Water Management Service	**Count**
Drinking Water Supply or Treatment	150
Wastewater Treatment	151
Urban Stormwater or Drainage Management	377
Watershed Management	288
Floodplain Management	251
Public Works	138
Transportation Infrastructure	82
Resilience or Sustainability Management	244
Emergency Management	100
Climate Scientist or Climate Modeler	124
Hydrologist or Hydrological Modeler	201
Other	73

Webinar reflections

"Great webinar — we work primarily by contracting experts, but we need to know what questions to ask, how to screen for the best modeling / engineering services. This helps a lot."

"This webinar series is my first exposure to what NOAA and local authorities are doing to address precipitation changes. It is extremely informative but comes quite fast, so I will need to rewatch, perhaps several times, to feel comfortable discussing the topic with those in my organization and community who are studying and/or considering making design standards changes."

"Webinar has been great! I'm an undergraduate student trying to figure out what I want to do exactly. Attending this webinar series has given me great insight as to what this sector looks like and the problems being faced right now. Super cool to see the intersection between climate science and urban planning!"

"Love it! We have really enjoyed the speakers and topics chosen and the level of detail of information presented, with basic topics and definitions and diving into actionable information. Really happy to be joining!"

"Need more of this where experienced folks in the field can connect and share ideas"

"Very important topic. Glad to see it given a complete treatment over the course of multiple presentations."

"The outcome of all this research saves public lives and requires an enormous investment in people and capital equipment ... So effectively communicating the urgency and "tell me what to do" information to the public closes the circle and sets the example by word and deeds for all the other counties to model."

"Their information is becoming an eye opener regarding changes with rain events."

"These have been great. I've enjoyed hearing the work completed by federal agencies to advance our understanding of the changing climate, as well as the policy impacts."