RESEARCH SPOTLIGHT

Holistic Flood Management Under Climate Impacts

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Municipalities and utilities are facing unprecedented challenges as they plan for extreme precipitation and flooding, which are becoming more frequent and less predictable. There was Hurricane Katrina in 2005, Superstorm Sandy in 2012, Hurricane Harvey in 2017, Hurricane Ida in 2021, and Hurricane Beryl in 2024.

In 2019, WRF, the New York City Department of Environmental Protection (NYCDEP), and the Water Utility Climate Alliance (WUCA) held a collaborative utility workshop on climate resilient planning. Participants from utilities and municipalities came to the following consensus as a collective workgroup:

"Intense precipitation events are occurring more frequently in many parts of the United States...and the frequency of such events is expected to increase as average global temperatures continue to rise. Even in regions where the frequency and intensity are not increasing, damaging and disruptive flooding, reduced drinking water and receiving water quality, and wastewater overflows put lives, property, and environmental assets at risk. In coastal regions, storm surge and sea level are compounding risks that can both cause and exacerbate serious flooding. These extreme events also have exposed important gaps in planning when it comes to effective urban stormwater and wastewater management in a changing climate."

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After the workshop, WRF published a project paper, "An Action Agenda for the Water Sector to Advance Methods for Achieving Integrated Climate Resilience," in 2020. The paper recognizes that a holistic approach to flood mitigation planning and modeling, including partnerships between stakeholders, is needed to balance competing management objectives while minimizing overall system vulnerabilities.

In May 2020, WRF funded a research project titled *Holistic Approaches to Flood Mitigation Planning and Modeling under Extreme Events and Climate Impacts* (5084). In parallel, WRF has been continuing several research projects on stormwater and flood management, with the goal to advance a holistic approach to wet weather flow and water quality management. In November 2023, the final report of WRF project 5084 was published and made publicly available.

Key Research Findings

Through a combination of a comprehensive literature review, utility surveys, utility interviews, and development of a user-friendly guidance document, WRF project 5084 accomplished the following:

- Developed a comprehensive summary of the state-of-the-practice with 15 utility case studies in North America and Europe for holistic flood management
- Defined data sources and modeling tools that enable a holistic approach to flood mitigation planning and modeling
- Demonstrated the application of selected methodologies most relevant to the needs of an integrated planning framework for flood management at the community level
- Synthesized findings into a guidance document based on holistic management approaches to planning for and mitigating climate change impacts

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- Served as a reference for utilities of all sizes to utilize the results for incorporating climate variability and uncertainty into their holistic flood management approaches

Case Studies Across Climate Regions

A series of case study interviews were conducted with participating utilities and agencies. Many of these organizations are leaders in understanding and addressing climate impacts and have valuable real-world experience with holistic flood planning. Seventeen utilities and municipalities (see Figure 1) were interviewed across the United States, Canada, and the United Kingdom, representing diverse hydro-climatology, socioeconomic and political climates, and flooding issues.

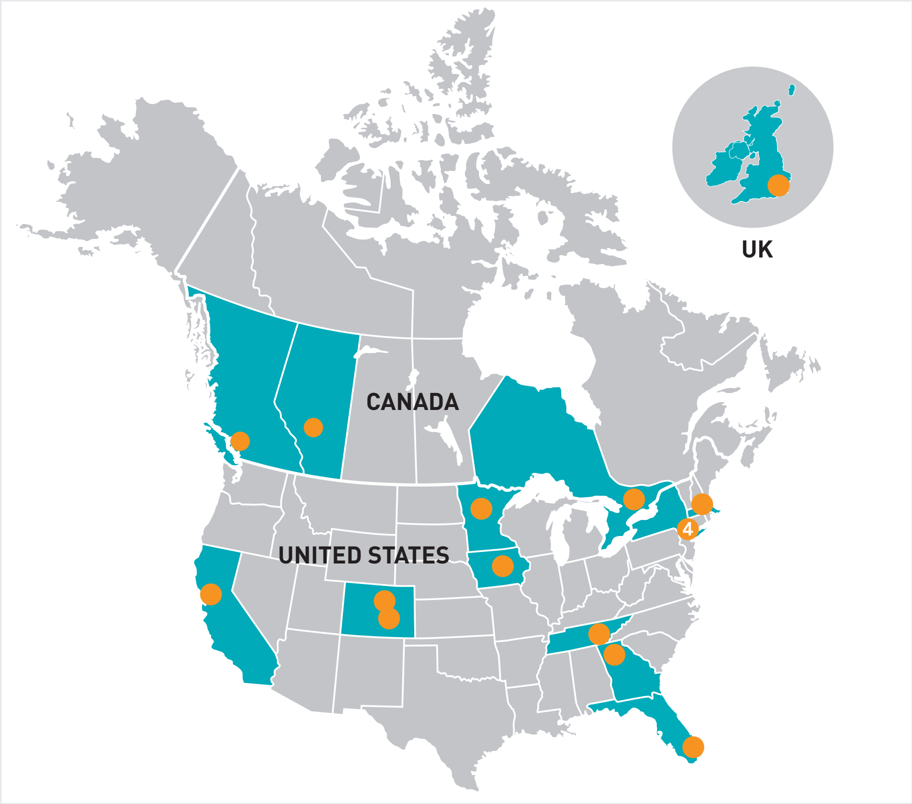

Figure 1: Location of Case Studies on Holistic Flood Management. Source: Adapted from Hersh et al. 2023 and Related Presentation (Prepared by Stantec).

There were a few recurring themes recognized throughout the interviews. Firstly, that major storms and related flooding tend to create public awareness, garner public support, and galvanize spending, but there is a limited window of opportunity to act on the attention. Secondly, high-intensity, short duration events such as smaller convective storms or thunderstorms at a sub-daily time step, colloquially referred to as "cloudbursts," can be very impactful to stormwater drainage systems and are hard to model and predict. Such storms can cause major flooding issues locally, often with little warning, and thus can make evacuations challenging.

Case studies found that major storms and related flooding tend to create public awareness, garner public support, and galvanize spending, but there is a limited window of opportunity to act on the attention.

- Many communities find value in ongoing, proactive (i.e., not project-based) partnerships with trusted local organizations and neighborhood groups.
- Many communities noted that land use development can have a greater impact than climate change. That is, increasing impervious cover has been a big issue with respect to flooding in their community.
- Wildfires are changing watershed hydrology, leading to higher runoff volume and intensity. Modeling has shown that for some regions (e.g., western United States), the former 100-year runoff event is now more representative of the 10- or 20-year runoff event. Challenges with fire are projected to increase as climate change leads to more common and severe fires.

With respect to incorporating climate change into the flood mitigation, communities seem to be using a wide variety of design events, probabilities, and approaches to understanding the compound effects of flooding. While some communities are studying or considering it, no case study participant is currently using joint probabilities of future coastal flooding or sea level rise, pluvial, water table, and fluvial events and impacts. Instead, many communities are using freeboard to provide a factor of safety to address uncertainty. In some communities, the freeboard is applied as an additional vertical buffer above the historical 100-year or 500-year design water surface elevation.

In addition, many communities now acknowledge that social vulnerability needs to be incorporated in flood risk analyses and management decisions, which leads to re-casting flood planning from a health and safety perspective instead of solely focusing on reducing economic damages. This new desire to "not monetize decision making" represents a possible paradigm shift in how flood mitigation planning is undertaken.

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Innovative Solutions to Holistic Flood Management Across Communities

Many communities that participated in case studies have recently developed Climate Adaptation and/or Climate Resiliency Plans. Of these plans, many include a multi-faceted discussion of flooding, heat impacts, urban forestry, and public health relating to climate adaptation measures, and many also included greenhouse gas emissions mitigation.

1 Green Infrastructure and Smaller Scale Storage

The Cities of Atlanta, New York, Metro Vancouver, and Hull, England have all implemented green infrastructure (GI) to achieve multiple benefits such as recreation, beautification, and urban heat island mitigation in addition to flood management. In addition, there are creative approaches to smaller scale storage via the concept of "fitting water wherever we can." Examples of this include installing strategic roadway medians to create micro-detention, re-crowning streets toward rain gardens, more use of blue and green infrastructure, and subsurface storage.

2 Early Warning System

Multiple case study participants, including the City of Toronto, New York City Housing Authority (NYCHA), Mile High Flood District (Denver, Colorado), Valley Water (Santa Clara, California), either have one or multiple operating flood warning systems or are planning to fund, develop, and implement a flood warning system soon. The Mile High Flood District established a fairly robust and progressing alert/flood warning system that has had positive results for the community in the last decade.

3 Land Development Policies

The City of Colorado Springs (CO) implemented a policy requiring all development greater than one acre to match the pre-development,

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historic 100-year flow rates across a full range of storms up to the 100-year event. Post-development runoff flow rates cannot exceed the pre-development across the full range of flows.

4 **Climate Change Action Plan and Climate-Resilient Guidance**
The Resilient Cambridge (MA) plan includes an urban forest master plan, a heat island assessment, and a flood/climate change vulnerability assessment. NYCHA and NYC have also developed similar plans, and Valley Water adopted a Climate Change Action Plan, which covers climate adaption and mitigation for the organization.

Another example is the Philadelphia Water Department (PWD)'s Climate-Resilient Planning and Design Guidance and associated policy. In 2022, PWD issued the Climate-Resilient Planning and Design Guidance. PWD requires that this Guidance be used in the planning, design, and construction of all PWD projects to the extent feasible, including drinking water treatment plants and water pollution control plants. Specifically, the PWD coastal design flood elevations are based on the following components: (1) Asset criticality; (2) Sea Level Risk (SLR) projections; (3) Storm surge; (4) A safety factor to account for (a) Wind waves; (b) Tidal amplification in the Delaware Bay; (c) Uncertainty associated with climate projections; (d) High tides above mean higher high water (MHHW); (e) Uncertainty in future local conditions (e.g., land use change, bathymetry changes).

Flood Answers and Questions (FAQs)

A user-friendly technical guidance document was developed as a series of "Flood Answers and Questions" (FAQs), formatted as Frequently Asked Questions. Users can quickly find answers to 70 questions in this document that span nine thematic groupings:

- **FAQ 1** – Flood Basics: Background on Flooding and Flood Risk
- **FAQ 2** – Methods to Determine Flood Risk
- **FAQ 3** – Considerations for Climate Change Impacts on Flooding
- **FAQ 4** – Flood Mitigation Planning
- **FAQ 5** – Incorporating Uncertainty into Flood Mitigation Planning
- **FAQ 6** – Leveraging Large Datasets and Novel Approaches for Flood Modeling and Mapping
- **FAQ 7** – Innovative Approaches to Flood Mitigation Planning
- **FAQ 8** – Stakeholder Engagement and Inclusion
- **FAQ 9** – Areas of Future Work

WRF's guidance document allows users to quickly find answers to 70 questions that span nine different areas of flood-related topics.

? Examples of FAQs for Utilities and Municipalities

1 **What Is NOAA Atlas 15? What Is the Connection between NOAA Atlas 14 and NOAA Atlas 15? How Might a Utility Decide Which One to Use?**
NOAA Atlas 15 is the proposed update to the modeling framework of the National Weather Service's authoritative precipitation-frequency analysis

product, commonly known as NOAA Atlas 14. The update would allow for the modeling of temporal non-stationarity and the integration of future climate projections. It will also provide continuous spatial coverage for the United States and affiliated territories using the most recently available precipitation observations and will provide enhanced supplemental products.

The proposed enhancements to the NOAA Atlas methodology include:

- Updating the statistical methodology to account for temporal non-stationarity.
- Adding new product features to account for future precipitation information from climate model projections, for example, providing adjustment factors based on the multi-model approach to account for the uncertainties associated with climate projections and future estimates.

NOAA Atlas 15 is in the planning stages, with a goal to complete the first version by 2026 or 2027.

2 How Can a Utility Leverage Machine Learning and/or Cloud Computing Resources to Enhance Traditional Flood Modeling and Mapping?
By integrating past engineering and science knowledge with data, machine learning (ML) provides a path towards finding new insights that expedite and enhance existing methodologies for characterizing flooding and climate risk. For flood modeling and mapping, machine learning could offer the following benefits:

- Finding results much faster than traditional approaches.
- Creating more accurate results, e.g., through combining earth observation data with traditional modeling results.

Machine learning has been leveraged to produce weather forecasts and predict flood mapping as accurate as large-scale models, but at a fraction

RELATED WRF RESEARCH

Economic Framework and Tools for Quantifying and Monetizing the Triple Bottom Line Benefits of Green Stormwater Infrastructure (4852)

Advancing Benefits and Co-Benefits Quantification and Monetization for Green Stormwater Infrastructure: An Interactive Guidebook for Comparison Case Studies (5105)

Mapping Climate Exposure and Climate Information Needs to Water Utility Business Functions (4729)

An Enhanced Climate-Related Risks and Opportunities Framework and Guidebook for Water Utilities Preparing for a Changing Climate (5056)

Integrating Climate Change Impacts with Wet Weather Management, Capital Improvement, and Stream Network Enhancement (5176)

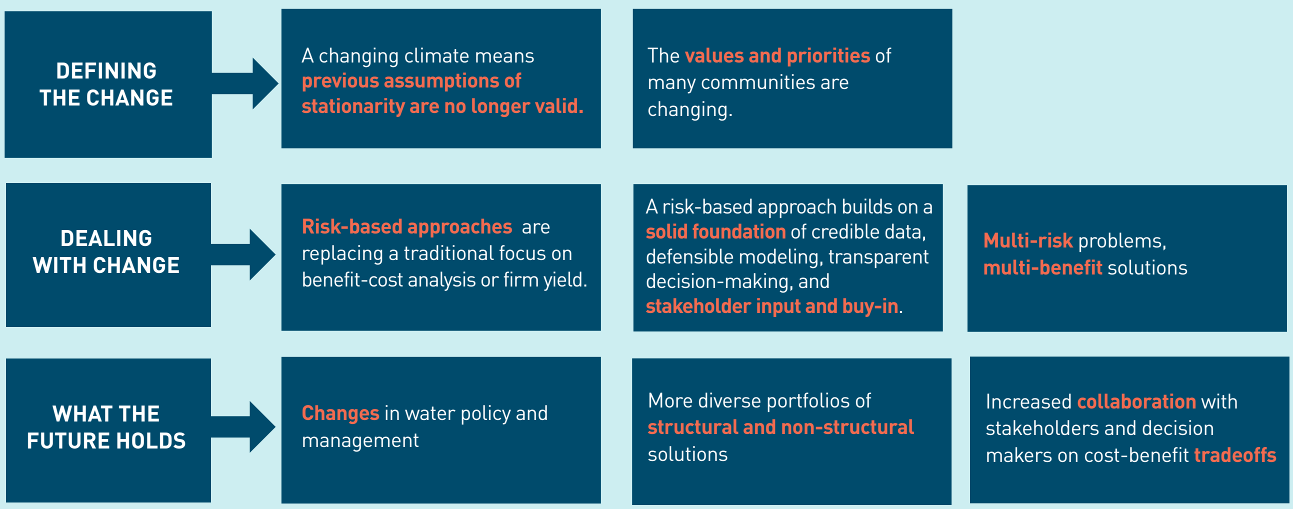
Enhancement of Resilience to Extreme Weather and Climate Events: Proactive Flood Management (4842)

of the cost. As such, ML modeling may also help support scenario-based planning by enabling multiple scenarios to be modeled rapidly to help inform decision-making.

Traditional flood modeling could be complemented by machine learning data-driven surrogate models that provide the following benefits:

- Ability to rapidly verify traditional modeling performance and consistency with other modeling approaches.
- Rapid extrapolation of physical modeling results in terms space and time to new areas and for new events (e.g., given a weather forecast).
- A path for increasing the resolution of risk of flooding by interpolating and extrapolating between existing traditional modeling output.
- The ability to transform and update traditional modeling results based on changes in climate, land use, or engineering infrastructure.
- A tool for enhancing traditional models by merging traditional modeling output data with earth observation data (e.g., observations of flood events), and in turn, using the enhanced output as a surrogate model to calibrate traditional modeling.

FIGURE 2. RISK-BASED APPROACH TO FLOOD MANAGEMENT



Looking into the Future for Holistic Flood Management

Changing conditions necessitate a new approach, and a changing climate means previous assumptions of stationarity are no longer valid. We are in a transition period when it comes to flood hazard modeling, mapping, planning, and mitigation. Similarly, the values and priorities of many communities are changing.

Utilities and municipalities need new tools and novel approaches to deal with this change. For many communities, risk-based approaches are replacing traditional benefit-cost analyses. A risk-based approach (Figure 2) works best when there is a solid foundation of credible data, defensible modeling, transparent decision-making, and input and buy-in from stakeholders throughout the entire process. In addition, there is a strong need to balance multiple water management objectives (e.g., water supply, recreation, navigation, hydropower, flood protection, ecosystem health, and water quality). Moving forward, it seems that we should see more diverse portfolios of both structural and non-structural solutions (e.g., codes and standards) and an increased benefit from collaboration with stakeholders and decision makers on cost-benefit trade-offs.

A successful flood mitigation management plan will not only require overcoming technical barriers such as modeling and accounting for uncertainty, but also communicating cost and benefits to the public in addition to collaborating across multiple sectors in a changing climate.

MORE INFORMATION

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