

America's Flooding Problem

Research and Innovation in Risk, Insurance, and Resilience

Edited by David J. Alexander, Ph.D.

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Abbreviations

AOI	Area of Interest
CFRSS	Community Flood Resilience Support System
DEM	Digital Elevation Model
DHS	Department of Homeland Security
DoD	Dates of Detection
FEMA	Federal Emergency Management Agency
FIMA	Federal Insurance and Mitigation Administration
FPNC	Flooding Post New Construction
GAO	Government Accountability Office
GPS	Global Positioning System
HMGP	Hazard Mitigation Grant Program
HPC	High Performance Computing
HSI	Human Systems Integration
III	Insurance Information Institute
IOT	Internet of Things
LIDAR	Light Detection and Ranging
MNDWI	Modified Normalized Difference Water Index
MSIFA	Multi-temporal Satellite Image-based Flood Analysis
NCRF	New Construction at Risk of Flooding
NDVI	Normalized Difference Vegetation Index
NFIP	National Flood Insurance Program
NLCD	National Land Cover Database

NOAA	National Oceanic and Atmospheric Administration
NUCI	National Urban Change Indicator
NWS	National Weather Service
OFE	Observed Flood Extent
OSM	OpenStreetMap
RD&I	Research, Development, and Innovation
SAR	Synthetic Aperture RADAR
S&T	Science & Technology
USACE	U.S. Army Corps of Engineers
WELL	Water Extreme Lookup Library



America's Fault Lines: Critical Issues Series Note

America's Fault Lines is a book series that maps the fractured geography of the United States through the lens of risk, power, and protection. It begins with two foundational volumes: ***Disaster Nation***, a diagnostic account of institutional failure and emergency misgovernance, and ***The New Geography of Homeland Security***, which reframes national security as a spatial project structured by five core geographies—sovereignty, power, risk, protection, and exclusion. Together, these anchor texts define the conceptual architecture of the series.

From this foundation, the series branches into five thematic clusters, each examining a critical fault line in the fragile American republic: systemic interdependence and cascading failure; civic fragility and domestic insecurity; borders, territory, and sovereignty; strategic surprise and institutional foresight; and the spatial politics of resilience and protection. A final set of instructional companion volumes grounds these ideas in applied practice, offering tools for spatial analysis, scenario planning, and the ethical use of GeoAI in homeland governance.

Across its volumes, the series rejects the idea that geography is neutral. It argues instead that space is produced through policy, data, infrastructure, and imagination and that the distribution of protection, security, and aid is neither accidental nor equal. America's Fault Lines provides both a critical lens and a strategic map for understanding the uneven geography of national security in the 21st century and for imagining what a more just and resilient republic might require.

Acknowledgements

This volume would not have been possible without the tireless commitment and collaboration of a broad community of researchers, practitioners, and public servants working at the forefront of disaster resilience and public safety innovation.

I would like to express my deepest gratitude to the contributors whose expertise shaped the content of this book. Each chapter reflects the insights of dedicated professionals who continue to advance the field through their research, policy engagement, and real-world impact. Your efforts have helped illuminate the path forward for a more flood-resilient nation.

Special thanks go to the DHS Science and Technology Directorate (S&T) for supporting this work and for fostering a culture of applied research that bridges science, technology, and public good. I also wish to acknowledge the members of the Flood Apex Research Review Board and the teams across federal, state, and local agencies who participated in pilot programs, technology evaluations, and stakeholder consultations. Your feedback and engagement ensured that this volume remained grounded in operational relevance and community needs.

To the editing and production teams, whose behind-the-scenes work made this book a reality, thank you for your careful attention and professionalism throughout this process.

Finally, to the countless emergency managers, engineers, scientists, first responders, community leaders, and residents working every day to protect people, places, and futures from the impacts of flooding—this book is for you.

— David J. Alexander, Ph.D.

FORWARD

Floods remain the most frequent, costly, and devastating natural hazard in the United States and worldwide. In an era of intensifying climate impacts, urban expansion, and aging infrastructure, advancing the science and practice of flood risk management has never been more critical. At every level of government, from local municipalities to federal agencies, the need for innovative, science-driven solutions to reduce flood risks is urgent and growing.

The Science and Technology Directorate (S&T) of the U.S. Department of Homeland Security has been a national leader in promoting and executing critical research aimed at enhancing flood resilience. Through thoughtful integration of requirements across key federal agencies—including the Federal Emergency Management Agency (FEMA), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Army Corps of Engineers—as well as collaboration with state and local governments and the first responder community, S&T has strengthened the nation's flood risk reduction efforts.

A keystone of this work was the Flood Apex program, an ambitious initiative that tackled many of the most pressing gaps in flood risk management. The Flood Apex program advanced low-cost flood warning sensor technologies harnessed the power of satellite platforms for flood detection and modeling, rigorously tested and validated floodproofing products, and pioneered improvements in flood risk modeling methodologies. Importantly, it also addressed the complex challenges associated with flood insurance, examining both private and public sector roles in protecting communities from flood hazards.

David Alexander, a critical leader and guiding force behind the Flood Apex Program, has meticulously compiled this groundbreaking initiative's public research, lessons, and technological advancements into this publication. *America's Flooding Problem: Research and Innovation in Risk, Insurance, and Resilience* offers an outstanding and accessible resource for floodplain managers, emergency officials, policymakers, engineers, and researchers.

Beyond chronicling past successes, this work serves as a blueprint for the future, showcasing how integrated science, technology, and policy innovation can meaningfully reduce flood risks and build stronger, safer, and more resilient communities.

David's leadership, vision, and dedication to advancing flood resilience will leave a lasting impact for decades to come. This book is an essential addition to every flood risk manager's toolbox—and a call to action for continued innovation and collaboration in the face of the evolving flood risk landscape.

— ***Dale A. Lehman, PE, CFM, President, Board of Trustees, ASFPM Foundation***
Madison, WI.

SECTION 1

Flood Research, Development, And Innovation In Homeland Security

Flooding has long been the most frequent and costly natural hazard in the United States—its impacts amplified by climate change, aging infrastructure, and growing development in high-risk areas. Recognizing that the stakes were no longer confined to localized emergencies, the Department of Homeland Security's Science and Technology Directorate (DHS S&T) launched a flagship initiative that would redefine the federal approach to flood resilience. This section introduces the origins, goals, and strategic design of the *Flood Apex program*, a transformative effort to align scientific research and technological innovation with the operational realities of homeland security and emergency management.

Developed in response to mounting evidence of the escalating human and economic toll of flood disasters, the Flood Apex program marked a critical turning point. DHS S&T no longer treated flooding as a purely environmental or emergency response issue; it was reframed as a core national security concern. Floods were recognized not only as threats to life and property, but as systemic risks that intersect with infrastructure protection, economic continuity, and community resilience. As such, the program sought to reduce key vulnerabilities: preventable loss of life, uninsured damages, and the costly delays in decision-making caused by fragmented data and outdated models.

Section 1 of this volume traces how national investments in flood science and technology evolved through this lens. It details the mission and institutional context of DHS S&T, explores the formation of the *Flood Apex research review board (RRB)*, and highlights the collaborative mechanisms used to ensure research met the needs of federal, state, and local partners. The program built strategic bridges—connecting the scientific community with agencies like FEMA, NOAA, and the U.S. army corps of engineers, and grounding research priorities in the real-world challenges faced by first responders, infrastructure managers, and public officials.

A central innovation of the program was the RRB, a multidisciplinary body of scientists, engineers, practitioners, and policy leaders tasked not just with peer review, but with shaping a living, responsive research agenda. Chapter two explores how this board became a cornerstone of the Flood Apex strategy, driving alignment between research outputs and operational needs while ensuring

scientific integrity and practical relevance.

Together, the chapters in this section set the stage for what follows. They underscore the core premise of this volume: that building effective, scalable flood resilience requires deliberate and sustained investment in *research, development, and innovation (R, D, & I)*. From smart sensor networks and advanced risk models to integrated decision-support systems and community-engaged planning tools, the Flood Apex program catalyzed a new model of science-enabled security. That model, and the lessons it generated, continue to shape the nation's evolving approach to disaster resilience.

DHS Science & Technology Directorate (S&T) and the Flood Apex Program

David J. Alexander[1]

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Abstract:

The Science & Technology Directorate (S&T) serves as the research and development arm of the U.S. Department of Homeland Security. It initiates strategic R&D initiatives to meet the demands of DHS Operating Components such as Federal Emergency Management Agency (FEMA) and respond to the evolving threat landscape, national priorities, and challenges facing the U.S. Flooding remains the most frequent and costliest disaster in the U.S. DHS S&T formulated the Flood Apex program to conduct foundational research and deliver novel technology solutions and innovations to flood risk challenges and operational problems and advance flood science and risk management. This chapter outlines the program research objectives, investment priorities, and intended outcomes.

Keywords:

Disaster Resilience, Homeland Security, Flood

1. U.S. Department of Homeland Security (DHS) Mission

Following the terrorist attacks occurring in the United States after September 11, 2001, President George W. Bush created the Office of Homeland Security within the Executive Office of the President to be led by Pennsylvania Governor Tom Ridge (DHS 2022). This office was tasked with coordinating a national strategy to safeguard the country against terrorism and respond to any future attacks, including considerations to the President for transforming the U.S. government to meet the changing nature of threats facing the Nation. This led to the submission in June 2002, by President Bush, to the U.S. Congress a proposal on the creation of the U.S. Department of Homeland Security (Bush 2002). With the passage of the Homeland Security Act of 2002, a few months later (November 25, 2002), the U.S. Department of Homeland Security (DHS) was established as a cabinet agency within the U.S. Government through the combination of all or part of twenty-two different federal departments and agencies (US Congress 2002). The newly formed, DHS encompassed five core mission sets: counterterrorism and homeland security threats, secure U.S. borders and approaches, secure cyberspace and critical infrastructure, preserve and uphold the Nation's prosperity and economic security, and strengthen the Nation's preparedness and

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resilience to all threats and hazards (DHS 2022). The Department's core was built upon the foundations of resilience to ensure a safe, secure, and prosperous Homeland (DHS 2022).

2. Science and Technology at DHS

"History shows that the United States has moved forward in astonishing ways thanks to national investment in basic research and advanced technology." (Meyer 2016).[2]

The dangers facing the U.S. are evolving as never before and becoming increasingly complex. These risks cross all Homeland Security mission areas, ranging from terrorism and emergency incidents such as chemical and biological attacks, global pandemics, active shooter, and violent extremism to natural hazards such as wildfires, earthquakes, superstorms, and floods exacerbated by global climate change (Alexander 2019). The Bush administration, in its proposal to create a Department of Homeland Security, recognized this evolving threat landscape, and more critically, the advantage that science and technology has played in the global ascendancy and leadership of the United States -- calling for the establishment of a national homeland security research and development enterprise (Bush 2002).

"In the war against terrorism, America's vast science and technology base provides us with a key advantage. The Department [DHS] would press this advantage with a national research and development enterprise for homeland security comparable in emphasis and scope to that which has supported the national security community for more than fifty years. The new Department would consolidate and prioritize the disparate homeland security related research and development programs currently scattered throughout the Executive Branch. It would also assist state and local public safety agencies by evaluating equipment and setting standards. integration of multiple models. A common refrain is that more than one model creates confusion, but a recognition that multiple models could be of value." (Bush 2002)

The nexus behind the Bush proposal was based on the rich history of public and private science and technology investment in the US. "Federal government spending on science and technology [has long been considered] an investment in national and economic security. It provides the underpinning of American prosperity, and provides critical national security capabilities, producing a larger economy in the future - generating wealth, jobs, tax revenue" (Atkinson and Ezell 2012). "If you take any major information technology company today, from Google to Intel to Qualcomm to Apple to Microsoft and beyond, you can trace the core technologies to the rich synergy between federally funded universities and industry research and development." (Peter Lee, vice president of Microsoft Research). All being told, over the last 65+ years, U.S. government funded science and technology has contributed to more than 2/3rds of the technologies that have had the most far-reaching impacts on society and the economy. How we work, eat, travel, communicate, trade, learn, play, and even care for our health today is a result of fundamental discoveries in thermodynamics, quantum mechanics, chemistry, physics, genetics, microbiology, and computer science, many of which were

[2] This is a quote came from a summer 2012 speech by Mitt Romney during his presidential campaign.

made only in the 20th century. Some of the most prominent examples are GPS, the internet, cell phones, and google search (Alexander 2019).

Congress instantiated the Bush administration's request for a homeland security research and development enterprise into the Homeland Security Act of 2002, as the Science and Technology Directorate (S&T), housed within DHS, led by an Under Secretary and serving as the science advisor and the research and development arm for the Homeland Security enterprise (US Congress 2002), S&T conducts basic and applied research, development, testing and evaluation activities in alignment with DHS missions. To accomplish this science mission, S&T provides evidence-based scientific and technical perspectives and executes strategic research, development and innovation programs (RD&I) to address a range of current and emerging threats—from aviation security to chemical and biological detection to critical infrastructure, resilience, climate and natural disasters, cybersecurity, and beyond (DHS S&T 2022).

3. Flood Apex Program

Flooding continues to be the most frequent and costliest disaster in the U.S. (FEMA 2019). Over the last 30 years, property losses from floods of all types have averaged $7.96 billion per year (III 2022). The loss trend is rising, and annual flood fatalities—unlike fatalities from other natural hazards—are not declining. These trends in flooding have been exacerbated by global climate change and economic development. Additionally, DHS, through FEMA, administers the largest single-peril, publicly managed disaster insurance program in the world, referred to as the National Flood Insurance Program (NFIP). The NFIP has about 5M flood insurance policies in force, covering approximately $1.2 trillion in property, and collects around $3.5 billion in insurance premiums annually. As of August 2017, the National Flood Insurance Fund was over $25 billion in debt to the US Treasury. The NFIP is a key risk transfer mechanism for the U.S., and it provides an important financial safety net for flood risk. FEMA also administers billions of dollars in pre- and post-disaster hazard mitigation programs such as the Building Resilient Infrastructure and Communities (BRIC), Hazard Mitigation Grants (HMGP), Flood Mitigation Assistance, Preparedness, and Resilience grants. These grant programs offer an important financial mechanism to state and local entities in making investments to strengthen U.S. preparedness and disaster risk reduction to flooding.

U.S. flood concern was one of the strategic RD&I efforts launched by DHS S&T in 2015 to meet the demands of DHS Operating Components, such as the Federal Emergency Management Agency (FEMA), the evolving threat landscape, national priorities, and challenges facing the U.S. (DHS S&T 2017). A formal program named Flood Apex was established a year later with input from a broad spectrum of flood resilience stakeholders that included an effort to solicit input from citizens and external organizations through an ideation drive held as a national conversation on the DHS website called "Disaster Proofing Society. Inputs from the national conversation on "Disaster Proofing Society" were compared to formal reports on national flood risk such as Government Accountability Office (GAO) reports, then

utilized to define the scope, goals, and objectives for the Flood Apex program.

For example, GAO Report 15-290, High Risk Series, stated (p.70) that Government-wide improvement is needed to reduce fiscal exposure to flooding in five areas, including, but not limited to, the federal government's role as:

- The leader of a strategic plan that coordinates federal efforts and also informs state, local and private sector action;
- The owner or operator of extensive infrastructure, such as defense facilities and federal property, vulnerable to climate impacts;
- The insurer of property and crops vulnerable to climate impacts;
- The provider of data and technical assistance to federal, state, local and private-sector decision makers responsible for managing the impacts of climate change on their activities; and
- The provider of aid in response to disasters. (US GAO 2015).

DHS S&T formulated the Flood Apex program as an outcome driven RD&I program. In other words, it was about delivering solutions to flood risk challenges and operational problems and not just advancing science. Figure 1 below depicts the overall Flood Apex program roadmap.

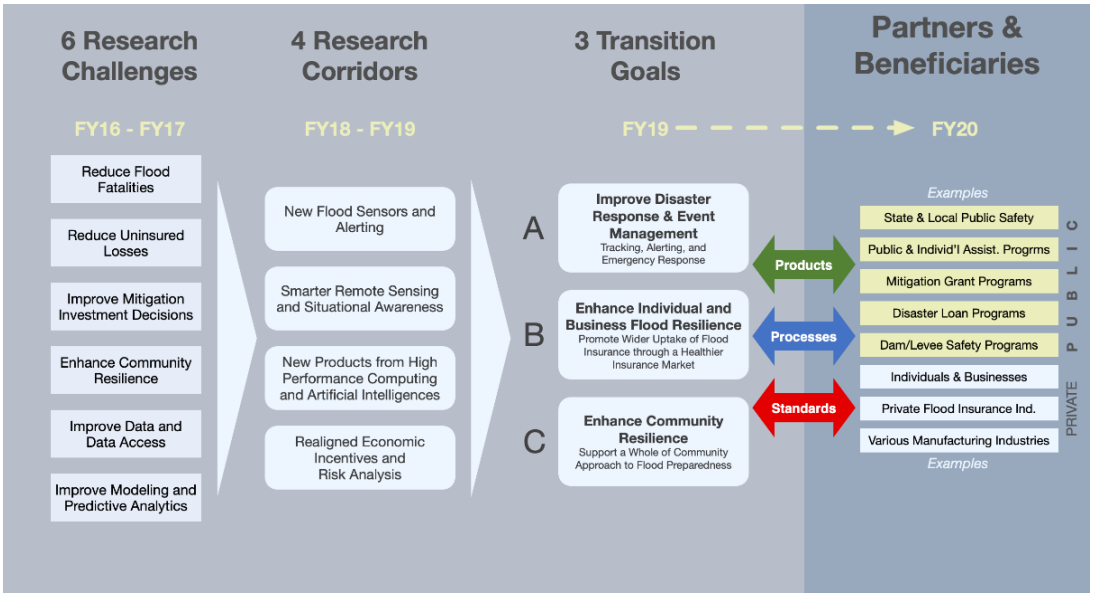


Fig. 1: DHS S&T Flood Apex RD&I Roadmap

The program was organized into six research challenges where limited RD&I investment could make a difference and support FEMA's 'moonshot' goals of doubling

flood insurance coverage (from 5 million to 10 million) by 2023 through both the NFIP and private insurance and quadrupling nationwide investment in mitigation by 2023. It was also supported by a multi-disciplinary research review board that provided a sounding board to S&T on the overall Flood Apex program and its RD&I activities. Complete descriptions of the six research challenges were:

1. Reducing flood fatalities: Flash floods kill more than 200 people each year (more than tornadoes), and on average, another 80 die in riverine or coastal floods. This death toll has remained steady over several decades. Flood Apex pursued research and development that it believed can help reduce these fatalities through new approaches in flood alerts and warnings, and through advances in information sharing at the local, state, and regional levels.
2. Reducing uninsured losses: About 9 million people live in flood hazard areas, and about half are uninsured or underinsured. Flood damages average $7.9 billion annually, and that figure is rising as climate change and urban development increase risks in flood-prone areas. Flood Apex believes that it can help develop and deploy new insurance risk products, based on emerging remote sensing technology and high-performance computing, that will allow the private insurance market to expand through better knowledge of structure-specific flood risks. More actuarially sound insurance can spur greater investment in consumer-level flood-proofing.
3. Improving mitigation investment decisions: Using federal grants and their funds, communities and individuals in flood hazard areas invest in dams and levees, buy up high-risk properties, rezone and replan land use to exploit natural flood defenses, and take other actions to avoid flood damage. Yet the data and the analytics they use to make these decisions are often flawed and incomplete. They don't necessarily know what properties are at risk or how much they are worth. They don't have an accurate idea of where floods will hit, or how severely. They don't know what mitigation options are available or how effective they will be. Flood Apex believes that the same technologies that can put the flood insurance market on a better footing will do essentially the same for community mitigation investments, improving community decision-making and expanding investment in targeted flood-proofing.
4. Enhancing community resilience: Communities' ability to bounce back after a flood depends on a host of factors, some behavioral (such as willingness to buy insurance), others institutional (such as community planning and preparedness), and others financial (such as access to grants or assistance). Maximizing resilience means protecting residential, commercial, and community infrastructure assets simultaneously, which is Flood Apex's goal. In addition to its involvement in improving insurance access and mitigation investments, the program's analytic tools can also help federal and state assistance programs focus financial relief more quickly and efficiently.
5. Improving flood data quality and access: Many of the above challenges relate directly or indirectly to the availability of accurate, current data in a form that is practically useful to the people who make flood-related decisions. That includes

consumers, community officials, insurance companies, and federal agencies. The challenge is not the quantity of data, if anything, too much information is available. The challenge concerns data accuracy, consistency, currency, uniformity of coverage across the nation, formats, presentation, and access. From a Human Systems Integration (HSI) perspective, there are concerns with data accessibility, readability, and relevance to the user's needs. In selected areas, Flood Apex believes it can help standardize data structures and improve access to key flood-related information at the national level.

6. Improving predictive analytics: Similar to the problem of getting accurate and current flood-related data into the right formats, presentations, and points of access, decision-makers at all levels need better predictive analytics. The time span of necessary predictions varies widely. For a flash flood, 20 minutes may not be fast enough to save lives. An extra day of warning can allow thousands to evacuate for a hurricane. But for a prospective homeowner, the period of interest is far longer: he or she wants to know how likely it is that a house will be flooded over the lifetime of its mortgage. Flood Apex is therefore reviewing the analytics arena, looking for areas where its investments can make a difference, or where it can repurpose analytic techniques from other domains.

The Flood Apex research challenges were further decomposed into four research innovation corridors targeted for execution and solution development, recognizing the growing convergence and interdependencies across the six research challenges. These corridors were described as:

- New Flood Sensors & Alerting - Traditional stream gauges to measure the height of streams are expensive, and permanent installations cost many thousands of dollars. Advanced manufacturing techniques can be used to produce lightweight, cheap, deployable, configurable, and internet-connected sensors to improve flood detection, monitoring, and local flood safety programs.
- Smarter Remote Sensing & Situational Awareness – current technology can deploy many new sensors into the skies — LiDAR to map the elevation of flood-prone areas down to the inch, high-resolution photography to identify vulnerable structures, and multispectral sensors to detect changes in the environment. Smarter exploitation of these capabilities can improve the detection of flooded areas, damaged structures, and at-risk infrastructure, reducing uninsured losses and lengthening response times for public safety.
- New Products from High Performance Computing - Supercomputing can do in minutes what old computers took months to finish. We can now process terabytes of data in minutes. Combining this super processing power with artificial intelligence can produce real-time forecasts and risk assessments that first responders can act on immediately to save lives and property and protect critical infrastructure
- New Economic Incentives & Risk Analysis - New data sources and powerful new, real-time analyses allow us to rethink the roles of government, the

insurance industry, and non-profits in planning for and mitigating the damage of floods. New ways to incentivize the private sector and individuals to take a more vital role in flood management can strengthen the community

All RD&I activities orchestrated under the Flood Apex program roadmap were ultimately aligned to three transition goals to optimize program value and help ensure solutions were delivered to key stakeholders and beneficiaries across the national flood resilience community. Full descriptions of the three transition goals were explained as:

A. **Improve Disaster Response and Event Management:** To improve response to flood events as they happen, the program focuses on flood detection, monitoring, alerting, emergency response, and recovery. The major activities under this theme relate to sensor-based alerting and improving first responders' access to the best, most critical information sources. Major considerations in flood alerting are the human performance aspects of the alert, its timelines, clarity, accuracy, unambiguity, differentiation from other ongoing alerts, compatibility with the skills of persons receiving the alert, contribution to their decision making, and enhancing their situation awareness. These are the activities that most directly relate to reducing flood fatalities, but they can also contribute to reductions in property damage, efficiency of evaluations, and improvements in community resilience following events.

B. **Enhance Individual and Business Flood Resilience:** The ability of individuals and businesses to recover after any flood event is primarily dependent on their private financial resources and on the investments, they have been able to make in advance to reduce risk. Flood Apex aims to increase insurance coverage of individuals and businesses, thereby increasing flood protection at the lowest, most granular level of economic risk. Major products include the data and analytics that will contribute to a National Structures Inventory, greatly improving the accuracy and precision of insurance underwriting. Other products include studies on increasing private sector involvement in the flood insurance market. These will help FEMA's Federal Insurance and Mitigation Agency (FIMA) revise policies and procedures to increase incentives for issuing unsubsidized flood policies, thereby reducing federal involvement. Finally, this area includes the development of resilience standards for flood-proofing products (semi-permanent barriers and sealants) that individuals and businesses can leverage to lower their own risk and thereby lower their insurance premiums by investing in property-level risk mitigation in advance.

C. **Enhance Community Resilience:** The third set of activities deals with flood risk at the community level, seeking to increase flood mitigation and resilience through a whole-of-community approach to disaster-proofing. The emphasis is on providing communities with better analytics with which to assess community risk and set cross-community priorities for flood mitigation investments. Outputs include data sets and risk models designed for non-

technical users and audiences. They also include a preparedness maturity model to help communities assess the quality of their flood preparedness and response capabilities.

4. Summary

Over the course of the 6-year lifecycle of the Flood Apex program, S&T executed numerous RD&I projects and activities. This volume is a compilation of the Flood Apex research roadmap and its subsequent outputs. It is organized into sections to best highlight the advancements in scientific knowledge and understanding, technology innovation, and state of practice of significance to the flood resilience community. These sections are enhancing flood safety and response, advancing flood resilience, closing the flood insurance gap, improving financial preparedness, and future-proofing society from floods.

5. Key Themes, Discussion Questions, and Additional Readings

5.1 Key Themes

Flooding continues to be the most frequent and costliest disaster in the U.S. Flood risk is being amplified by climate change, economic development, and demographic shifts. Persisting.

Addressing U.S. flood risk requires a blend of technology solutions and innovations, partnering with a diverse set of stakeholders, and action at the national, state, and local level.

S&T is the research and development arm of DHS, providing a key advantage to the Department in addressing the evolving threat landscape, associated risks and disaster preparedness needs of the Nation.

5.2 Discussion Questions

What are the leading causes of flood fatalities in the U.S.? How might flood risk management approaches be improved to reduce flood fatalities?

What are the leading causes of flood property damage and losses? How many of those losses are uninsured? What are the barriers to flood insurance uptake? What tools can be developed to promote the uptake of flood insurance?

Flood mitigation is an effective approach to flood risk management. How might flood mitigation investment decisions be improved?

What are the leading indicators of community resilience?

How might flood information and access be improved? What are the gaps and limitations in flood risk data?

5.3 Additional Readings

DHS Flood Apex Video - https://youtu.be/nboC-u2iMTE

DHS S&T Flood Apex Program page - Flood Program | Homeland Security (dhs.gov)

DHS S&T Flood Apex Program Factsheet - https://www.dhs.gov/sites/default/files/publications/Flood-Apex_Rethinking-Americas-Costlist-Disaster-Fact-Sheet_v1-508%281%29.pdf

FEMA Flood Maps - Flood Maps | FEMA.gov

FEMA Floodplain Management Community Rating System - Community Rating System | FEMA.gov

FEMA Community Preparedness Flood Protective Action Guidance - Flood (fema.gov)

GAO Report 15-290, High Risk Series, National Flood Insurance Program - GAO-15-290, HIGH RISK SERIES: An Update

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History and Role of the Flood Apex Research Review Board

*Thomas W. Richards*on[3]

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Abstract:

The Flood Apex program was launched by DHS S&T in 2016 to address challenges stemming from the increasing complexity and risks of flooding in the U.S. To support the program, a multidisciplinary Research Review Board (RRB) was established within the DHS Coastal Resilience Center of Excellence to offer access to subject matter experts, diverse viewpoints, and candid feedback on the program's R&D activities, while providing a venue for sharing and discussing the latest advances in flood science and their application to DHS missions. This chapter provides an overview of the Flood Apex RRB, its role, contributions, and impacts on program success and outcomes.

Keywords:

Research review board, center of excellence, resilience

1. Introduction

"If I have seen further, it is by standing on the shoulders of Giants." (Newton 1675)[4]

In launching the Flood Apex program, DHS S&T leveraged the DHS Coastal Resilience Center of Excellence (CRC) to create a Research Review Board (RRB) designed to bring together a cross-section of renowned experts, serving as a strategic sounding board to the agency. The RRB was envisioned as a mechanism not only to strengthen the scientific and technical foundation of the program but also to ensure that research efforts remained tightly connected to the operational realities faced by communities, first responders, and policymakers. Its purpose was twofold: to a) document the history and evolution of the Flood Apex Program Research Review Board and b) summarize its

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[4] Sir Isaac Newton espoused this most famous quote in a letter to Robert Hooke in 1675, According to Robert Merton, this statement is often used to symbolize scientific progress. Robert Merton examined the origin of this metaphor in his 1965 book *"On the Shoulders of Giants."*

contributions to ensuring program performance and helping deliver impactful outcomes.

2. History and role of the RRB

The RRB was officially established in August 2015 by the Coastal Resilience Center, a DHS Science and Technology university center of excellence headquartered at the University of North Carolina at Chapel Hill. The CRC performed a range of management and administrative functions for the RRB throughout its five-year life. These included developing and maintaining the RRB Charter, recruiting and vetting members, acquiring and archiving Non-Disclosure Agreements (NDAs) to protect sensitive program information, and, where appropriate, reimbursing travel expenses and providing meeting stipends for eligible members.

Recognizing the need for consistent leadership and subject matter depth, the CRC contracted with WaterWonks LLC to provide an RRB chairperson, Dr. Sandra Knight. Dr. Knight brought extensive experience from her time at FEMA and academia and took an active role in guiding the RRB's work. In addition to presiding over formal meetings, her duties included developing draft agendas, facilitating discussions, capturing meeting notes and minutes, and providing expert insight on technical and policy matters.

The RRB operated through a deliberate mix of virtual and in-person meetings, with meeting cadence and format tailored to evolving program needs. Membership evolved over time as well, reflecting both natural turnover and a strategic effort to maintain the right blend of technical skills, operational experience, and innovative thinking. Approximately half of the 2020 members had served since the RRB's inception, ensuring a critical balance between continuity and fresh perspectives.

The nature of the RRB's work shifted in response to the Flood Apex Program's evolution. Early agendas focused heavily on defining the program's strategic scope, clarifying its target end-users and beneficiaries, and refining the technical objectives outlined in the initial program framing documents. As the program matured, RRB meetings transitioned toward more detailed technical reviews of specific research deliverables and pilot products. Some sessions required members to execute NDAs, particularly when reviewing proprietary contractor work or preliminary field data not yet ready for public release.

The RRB's final planned meeting was designed to coincide with the 8th International Conference on Flood Management (ICFM8), scheduled for August 2020 in Iowa City, Iowa, as part of the 100th anniversary celebration of the Iowa Institute of Hydraulic Research. In addition to hosting a final in-person meeting, RRB members were to help organize and participate in two special conference sessions showcasing key advances from the Flood Apex portfolio. Unfortunately, the COVID-19 pandemic forced the postponement of ICFM8, requiring the RRB's final meeting to be held virtually. Despite the shift, members maintained robust engagement, with special focus on refining and delivering conference presentations that highlighted the Flood Apex Program's contributions to the broader flood resilience community.

While fulfilling its formal advisory responsibilities, the RRB also evolved into something more, a unique, interdisciplinary forum where leading voices from engineering, hydrology, emergency management, finance, insurance, and policy could exchange perspectives, challenge assumptions, and forge lasting professional relationships. This collegial spirit of mutual respect and intellectual curiosity was not explicitly mandated by the RRB's Charter but emerged organically over time. Through active participation and thoughtful management, the RRB transitioned from a collection of individual reviewers into a trusted, collaborative advisory body.

This transformation carried tangible benefits for the Flood Apex Program. As trust deepened among members, their feedback became more nuanced, strategic, and operationally grounded. Program leadership increasingly used the RRB not merely for scheduled reviews but as an agile sounding board for emerging ideas, challenges, and opportunities. The success of this model suggests that other large-scale DHS research initiatives could similarly benefit from the deliberate cultivation of a dynamic, trusted advisory body rather than relying solely on episodic, formal reviews.

3. Key Themes, Discussion Questions, and Additional Readings

3.1 Key Themes

Flooding is a multidimensional problem that demands cross-disciplinary research and expertise. The Flood Apex Program benefitted immensely from the diverse perspectives, candid dialogue, and iterative feedback provided by a committed Research Review Board, which strengthened program formulation, execution, and research outcomes across its five-year life.

3.2 Discussion Questions

What is the appropriate role for a research review board to support strategic R&D initiatives?

How might a research review board be structured to be most effective, both in providing technical rigor and fostering innovation?

3.3 Additional Readings

DHS Coastal Resilience Center Flood Apex Program web page - Flood Apex Program - Coastal Resilience Center (unc.edu)

DHS Coastal Resilience Center 2021 Annual Meeting, Flood Apex Program recap - 2021_annual_meeting_Knight_Flood-Apex.pdf (unc.edu)

Section 2

Enhancing Flood Safety and Response

As weather-driven flood events grow in frequency, severity, and spatial reach, they test the limits of our emergency response systems. From sudden inland flash floods to protracted coastal inundations, these events demand far more than localized interventions; they require coordinated, technology-enabled action across agencies, jurisdictions, and sectors. Section 2 of this volume shifts the focus from national R&D strategy to the operational edge: the front lines of disaster response where lives are saved—or lost—based on the speed, accuracy, and coordination of action.

This section explores how innovation, mutual aid, and systems integration are transforming the practice of flood preparedness and emergency management. It highlights the critical role of *interoperable technologies, shared situational awareness platforms, and collaborative capacity-building effort*s in equipping responders and communities to act decisively during complex flood events. Contributions in this section trace a range of field-ready solutions—from low-cost sensor deployments to cloud-based analytics—that bring the promise of science into real-time application.

Flood response today is not bounded by city limits or county lines. Recent disasters such as Hurricanes Harvey, Florence, and Ida revealed how flooding cascades across regions, overwhelms interconnected infrastructure, and strains even the most seasoned emergency systems. In response, the Department of Homeland Security's Science and Technology Directorate (DHS S&T) has pioneered tools and pilot programs aimed at bridging the gaps between hazard detection, operational decision-making, and life-saving intervention.

This section opens with a chapter on *innovation and mutual aid*, examining how resource-sharing architectures and pre-established trust networks can scale effectiveness during response. It details how pre-positioned data tools, joint training exercises, and interoperable command platforms support readiness across the public safety enterprise—from emergency managers and dispatchers to firefighters, law enforcement, and utility operators.

Subsequent chapters spotlight DHS-supported efforts such as the *National Flood Preparedness Guidelines for First Responders*, drawing on insights from multi-state pilots and operational exercises. These guidelines codify flood-specific protocols for response agencies and embed geospatial technologies into workflows to improve readiness and responsiveness. Additional case studies from *North Carolina and Kentucky* showcase how low-cost sensors and GIS-linked alert systems are enabling faster detection and more informed local decision-making. One chapter focuses on *dam safety*, a critical but

under-addressed element of flood risk—highlighting how improved modeling tools are advancing awareness and downstream evacuation planning.

The section concludes with a look at the *Water Extreme Lookup Library (WELL)*, a next-generation cloud-based analytics tool that delivers rapid flood impact assessments using high-resolution models and real-time data feeds. Designed for emergency operations centers and field teams alike, WELL exemplifies how advanced analytics can accelerate situational awareness and direct resources where they are most needed.

Together, these contributions underscore a fundamental shift: that effective flood response now hinges as much on *data, integration, and communication* as on physical assets or personnel. While Section 1 established the scientific and strategic underpinnings of the Flood Apex Program, Section 2 brings that vision to life in the field—under pressure, across systems, and with lives on the line. It reaffirms a critical lesson of modern emergency management: resilience is no longer a static goal, but a dynamic process that depends on our ability to *innovate, coordinate, and adapt* in the face of cascading crises.

Innovation, Capacity Building, and Mutual Aid Coordination for Disaster Resilience

Rebecca Harned[5]

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Abstract:

Mutual is critical to unified response during emergencies and is becoming more acute as disasters become more extreme and complex, involving multiple organizations, and crossing many jurisdictional boundaries. Despite the growing recognition of the importance of mutual aid, the emergency management community is facing significant challenges. This project sought to explore these challenges through a national mutual aid technology exchange with key stakeholders and practitioners. Several themes emerged in the process ranging from technology information sharing and interoperability, capacity building, innovation, and coordination issues. Additionally, it provided a benchmark assessment of current progress and opportunities to advance the Mutual Aid community leveraging a flood disaster scenario.

Keywords:

Capacity building, mutual aid, crisis management

1. Introduction

"By failing to prepare, you are preparing to fail." (Williams 1919) [6]

Crisis management consists of planning for and responding to emergency incidents that might occur. As incidents change in size, scope, and complexity, the response must adapt to meet requirements. Many incidents exceed the capacity and capabilities of a jurisdiction and necessitate the use of mutual aid—the sharing of capabilities in the form of resources and services upon request.

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[6] This quote first appeared in Biblical World 1919. Volume 53, Number 1, Religious Education, (Excerpt from "The Group Plan" by Rev. H. K. Williams in the "Young People's Service", Start Page 80, Quote Page 81, Column 2, The University of Chicago Press, Chicago, Illinois.

Public safety officials and first responders need access to innovative and standardized technology solutions for daily operations that can scale to support large-scale incidents, involving more complex resource management and mutual aid.

Since September 2018, the Department of Homeland Security (DHS) Science and Technology Directorate (S&T) partnered with the National Alliance for Public Safety GIS Foundation (NAPSG) and engaged with the public safety community to address some of the most pressing needs and requirements around innovative technology and capacity building for mutual aid. Building from past efforts, lessons learned, and recent disasters, this effort sought to remain grounded in the daily realities of first responders across the nation. This effort successfully identified and addressed needs and requirements through the following initiatives:

1. Providing the community with benchmarks to form a baseline of information sharing capabilities, resource management systems, and mutual aid processes.
2. Identifying information sharing standards to improve interoperability.
3. Providing planning tools.
4. Identifying needs and coordinating, testing, and evaluating crisis management and mutual aid technology.
5. Hosting forums for the community to share best practices and advance mutual aid.

This report covers the progress made in these areas across a three-year span and identifies remaining requirements and challenges uncovered through engagement with the public safety community.

1.1 Context

To gain a current picture of crisis management and mutual aid operations and to define a common vision for unified resource management policy, implementation, and technology enablement, a summit of 20 policy level leaders representing federal, state, local, and tribal agencies and relevant NGOs was hosted by DHS S&T and FEMA in 2019. Stakeholders indicated that local resource management was operating better than ever, and that mutual aid had worked well in many recent incidents. Local and regional mutual aid was used daily and provided the framework of neighbor-helping-neighbor.

Despite these successes, challenges still existed in resource management and mutual aid operations, particularly related to interoperability. Lack of coordination and integration between various organizations, resource management initiatives, and technology systems were major impediments to achieving unified and cohesive resource management and mutual aid. While the public safety community confirmed their access to more technology than ever before, a challenge remained with the ability to interoperate between systems and exchange appropriate information and data.

1.2 Benchmarks for Information Sharing Capabilities, Resource Management Systems, and Mutual Aid Processes

With rapid changes in mutual aid and crisis management technology, forming a baseline understanding of how mutual aid is conducted and determining information sharing capabilities is critical. Overarching systems that do not consider the daily

realities and business operations of state, local, tribal, and territorial (SLTT) partners are destined to fail, especially with rapidly evolving technology and an increased demand for local authoritative data.

Four surveys and products were developed to help explore this baseline and inform future priorities:

- The Resource Management Maturity Study (RMMS)
- The Information Sharing Assessment Tool (ISAT)
- The Capability and Readiness Assessment Tool (CARAT)
- The Technology-Related Roles within National Incident Management System (NIMS) Structures Study

1.2.1 Resource Management Maturity Study (RMMS)

The RMMS was conducted to form a baseline understanding of the extent of implementation of resource typing, inventorying, and management across the nation. The study report includes recommendations on maturing resource management nationwide. Findings from this effort have helped inform resource management guidance and technology investments that are part of NIMS and various resource management and mutual aid systems commonly in use today.

1.2.2 Information Sharing Assessment Tool (ISAT)

The ISAT is an easy-to-use tool for public safety officials and first responders from across the nation to identify their own information-sharing capabilities and gaps. The ISAT aims to empower communities to develop an action plan to:

Access the ISAT at https://www.napsgfoundation.org/isat/.

- Address their most pressing information-sharing gaps.
- Publicize their progress and achievements.
- Facilitate interagency and cross-discipline information sharing discussions among partners.

Developed by DHS S&T with guidance from public safety practitioners nationwide, the ISAT allows organizations to gauge their information sharing capabilities against different scenarios, providing scores across the Interoperability Continuum.

1.2.3 Capability ad Readiness Assessment Tool (CARAT)

CARAT is a self-assessment tool to gauge an organization's geospatial capabilities. It is designed to provide organizations with guidance to increase geospatial maturity. The online self-assessment provides practitioners with questions to determine their organizational maturity in six common geospatial areas:

Access the CARAT at https://www.napsgfoundation.org/carat/.

- Governance
- Standard Operating Procedures
- Staffing
- Technology

- Training and Exercises
- Usage

1.2.4 Technology-Related Roles within NIMS Structures Study

The goal of the Technology-Related Roles within NIMS Structures Study was to form a baseline understanding on how information technology, cyber security, geospatial, and communications roles and functions are structured within emergency operation centers (EOC) and Incident Command System (ICS) organizational structures across the nation at all levels of government. The study helps inform national guidance and guidelines regarding the definition and placement of technology, communications, and cyber security roles and functions within incident management structures.

Access the Technology-Related Roles within NIMS Structures Report at https://arcg.is/DvW8q.

2. Information Sharing Standards

A variety of technologies and products are available for use by the public safety community in supporting incident management and mutual aid. The public safety community continues to experience challenges carrying out the functions identified above—not because of a lack of technology, but due to the insufficient use of interoperability and information exchange standards between systems.

To help address this gap, DHS S&T spearheaded the development of Guidance on Incident Management Information Sharing Standards. The goal of the information sharing guidance is to aid the public safety community in the acquisition, selection, and development of incident management technologies that apply information sharing requirements and standards.

The goal of the information sharing guidance is to aid the public safety community in the acquisition, selection, and development of incident management technologies that apply information sharing requirements and standards. Access the Job Aid on Incident Management Technology https://arcg.is/TeKnC

The guidance identifies relevant standards for incident management and mutual aid requirements with a focus on information exchange for different types of emergency management systems that support incident management and mutual aid functions. The guidance includes standards-selection workflows and decision maps to aid technologists and leaders in choosing the appropriate information sharing standard for a given need.

The guidance was baselined in 2019 and updated in 2020 and 2021. The latest revision of the guidance includes two documents—a job aid geared toward leaders and a technical guide geared toward technologists and vendors. An interactive web-based version of the job aid is also available.



Fig 1: Screenshot of the Interactive, Web-Based Job Aid

3. Planning Tools

3.1 Resource Management Planning Tool

Public safety stakeholders identified the need for mutual aid and crisis management systems to be equipped with a risk analysis-based resource planning suite of tools or capability. This is routinely identified as a critical need so that risk information can be integrated into the operational workflows that these systems support. Further, the integration of a core set of data and analysis-rich resource planning tools within existing mutual aid and crisis management systems can enable operators and decision makers to support the natural progression of decision making starting in clear skies and seamlessly moving into response and recovery.

Access the Resource Management Planning Tool https://www.napsgfoundation.org/resources/rmpt/.

In 2019, a preliminary review and assessment was completed that included existing planning tools, data, and indices to ensure a common baseline understanding of existing capabilities. A temporary Mutual Aid Planning Tools Working Group was formed that identified and prioritized user requirements for mutual aid planning capabilities. Available mutual aid planning tools and disaster datasets were reviewed against stakeholder requirements. It was concluded that the mutual aid planning tool needs identified by the working group were not being met.

To address this gap in technology offerings for mutual aid planning, a preliminary version of the Resource Management Planning Tool was developed and released, to include both a hosted version and public source code in a GitHub repository. The tool

was also integrated into the National Mutual Aid System (NMAS) for access within a technology platform used to manage mutual aid operations by first responders.

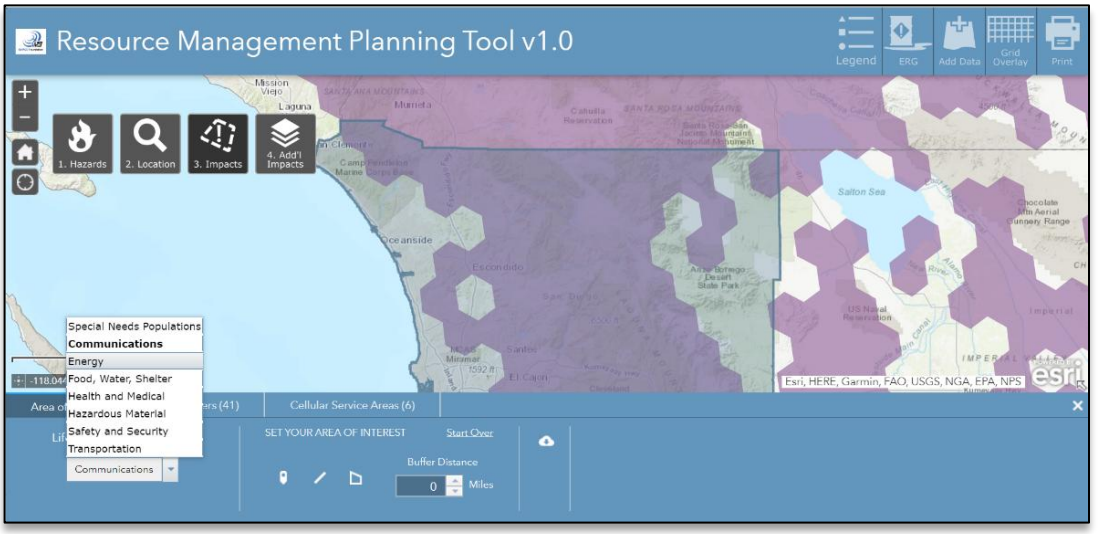


Fig 2: Screenshot of the Resource Management Planning Tool

3.2 Guidance on Risk, Resilience, and Vulnerability Indices

Understanding a community's risk, resilience, and vulnerability is vital for effective disaster management and resource planning. An increase in the number of available indices that measure these factors prompts confusion over which index to use, when to use it, and for what purpose.

Access the Guidance on Risk, Resilience, and Vulnerability Indices at https://www.napsgfoundation.org/resources/indices-guidance/.

NAPSG Foundation, in partnership with the Urban and Regional Information Systems Association's (URISA's) Community Resilience Task Force, launched a study to understand available and emerging risk, resilience, and vulnerability indices as the basis for developing guidance to help the emergency management community match business needs with specific indices. The study led to the development of guidance to assist the public safety community in quickly understanding which indices are available, the data and methodologies behind them, and their relevance for use in preparedness and response.



Fig 3: Screenshot of the Online Guidance on Risk, Resilience, and Vulnerability Indices

3.2.1 Progress and Opportunities

The Guidance on Risk, Resilience, and Vulnerability Indices currently features five nationwide indices:

- CDC Social Vulnerability Index (SVI)
- Social Vulnerability Index for the United States (SoVI®)
- Community Resilience Indicator Analysis (CRIA)
- Baseline Resilience Indicators for Communities (BRIC)
- National Risk Index (NRI)

These indices are presented in the guidance through both detailed descriptions and comparison charts.

While the guidance is useful and applicable in its current form, additional indices may be analyzed and included, increasing the robustness of the guide. Also, the addition of workflows and decision charts could aid the public safety community in choosing the appropriate index for their business needs.

3.3 Advising the Development of the National Resource Hub

To support the whole community in implementing resource management, FEMA provides the National Resource Hub. The National Resource Hub is a suite of web-based tools that supports a consistent approach for the resource management preparedness process and serves as a no-cost solution for all SLTT agencies and NGOs. Systems include the Resource Typing Library Tool (RTLT),

National Resource Hub

Access the National Resource Hub at https://preptoolkit.fema.gov/web/n

Resource Inventory System (RIS), and OneResponder (a personnel qualifications and credentialing management system).

DHS S&T collaborated with FEMA in the ongoing development of the National Resource Hub to determine appropriate processes and resources for the development and integration of legacy systems and data. This collaboration has helped inform and align developed resources with stakeholder input and practice, and it has provided continuity across stakeholder engagements and development work.

3.3.1 Progress and Opportunities

The National Resource Hub has been treated as a technology system thus far. It offers a no-cost resource management preparedness solution for all SLTT agencies, NGOs, and other mission partners while ensuring organizations and resource owners retain full ownership and control over their resources.

The community has signaled a clear need for the National Resource Hub to expand beyond a technology offering to become an overarching set of guidance and an environment for information sharing and interoperability across resource management and mutual aid systems. While the technology component remains an important piece of this overall strategy, particularly for smaller and less-resourced organizations, options for information sharing must be guided and made available to the whole community without requiring the use of a specific technology tool.

Advancements have been made with the National Resource Hub, particularly with the release in 2021 of restricted-access application programming interfaces (APIs) and data services to provide resource inventory and personnel qualifications management data to select third-party systems. The National Resource Hub technology may serve as a model and pilot from which to develop more widely applicable guidance and strategic visioning.

4. Crisis Management and Mutual Aid Technology Coordination, Testing, and Evaluation

For technology to be successful, it must align with business practices and address the needs of practitioners. Engaging with the public safety community to elicit requirements and test and evaluate crisis management and mutual aid technology is of vital importance.

Avenues for practitioner engagement:

- National Resource Management Summit
- NIC Coordination Group
- NCG Technology Sub-Group
- National Mutual Aid Technology Exercise

The following avenues for practitioner engagement were facilitated through the support of DHS S&T over the course of this three-year effort. Each avenue provided useful insight into stakeholder needs and helped advance the development and implementation of select crisis management and mutual aid technology.

4.1 National Resource Management Summit

In 2019 and 2021, leaders representing federal, state, local, and tribal agencies and relevant NGOs met to define a common vision and mission-critical requirements for resource management across policy, implementation, and technology domains.

While technology capabilities continue to advance, challenges continue to be identified surrounding the interoperability of systems due to:

- the need for guidance and governance for sharing appropriate resource information,
- a lack of knowledge within smaller and local jurisdictions about existing guidance and governance due to the limited extent of outreach and education at this level, and
- the culture of establishing mutual aid agreements through personal relationships rather than a needs assessment.

4.2 NICS Coordination Group and Technology Sub-Group

Stakeholders at the spring 2019 National Resource Management Summit identified the need for a well-defined and neutral coordinating body to be established to provide guidance in resource management policy, communication, and coordination across disciplines and levels of government for the core emergency services. The stakeholders championed the concept of a National Integration Center (NIC) Coordinating Group (NCG). They recommended the NCG work to unify resource management practices towards achieving interoperable and seamless mutual aid operations across the core emergency services and among all levels of government.

The NCG launched in 2019 and serves as a standing working group of experts from SLTT and federal agencies and NGO partners. The NCG strives to identify areas of collaboration and enhance unity of effort by providing a forum to exchange viewpoints, gain a broader national perspective on emergency management issues, and increase transparency across the whole community.

The NCG Technology Sub-Group is one of seven standing sub-groups of the NCG. This sub-group consists of technology subject matter experts (SMEs) across a variety of SLTT and federal agencies and NGO partners. The group focuses on addressing whole community NIMS-related technology issues and identifying areas for improvement. The NCG Technology Sub-Group has spearheaded several different efforts to include establishing a baseline understanding around specific NIMS-related practices across the nation and developing guidance, resources, and technology recommendations to advance the proper use of technology within public safety.

4.2.1 Progress and Opportunities

Since its launch in 2019, the NCG Technology Sub-Group has addressed the following activities:

- Analyzed select resource management practices and emergency operations across the nation.
- Developed EOC virtualization guidance.
- Reviewed and updated select position qualifications and resource typing definitions within RTLT and identified gaps.

- Identified functional requirements for NIMS and NQS technology tools.

4.3 National Mutual Aid Technology Exercise (NMATE)

During the 2019 National Resource Management Summit, stakeholders identified the need to plan and conduct an annual resource, crisis management, and mutual aid technology interoperability exercise to test and evaluate process in increasing appropriate data sharing among systems.

> The needs for a cohesive, nationwide **resource management information exchange framework** and guidance to support appropriate information sharing remains a major gap from both NMATE 2019 and 2021.

To address this finding and need, DHS S&T worked together with FEMA in planning and conducting two instances of the National Mutual Aid Technology Exercise (NMATE) in 2019 and 2021. Each event brought together over 20 technologists, first responders, and leaders representing federal, state, and local agencies; relevant NGOs; and development organizations. The NMATE series builds from past efforts and is designed to maximize the operational viability of the Nation's investments in technology systems used in resource management and mutual aid.

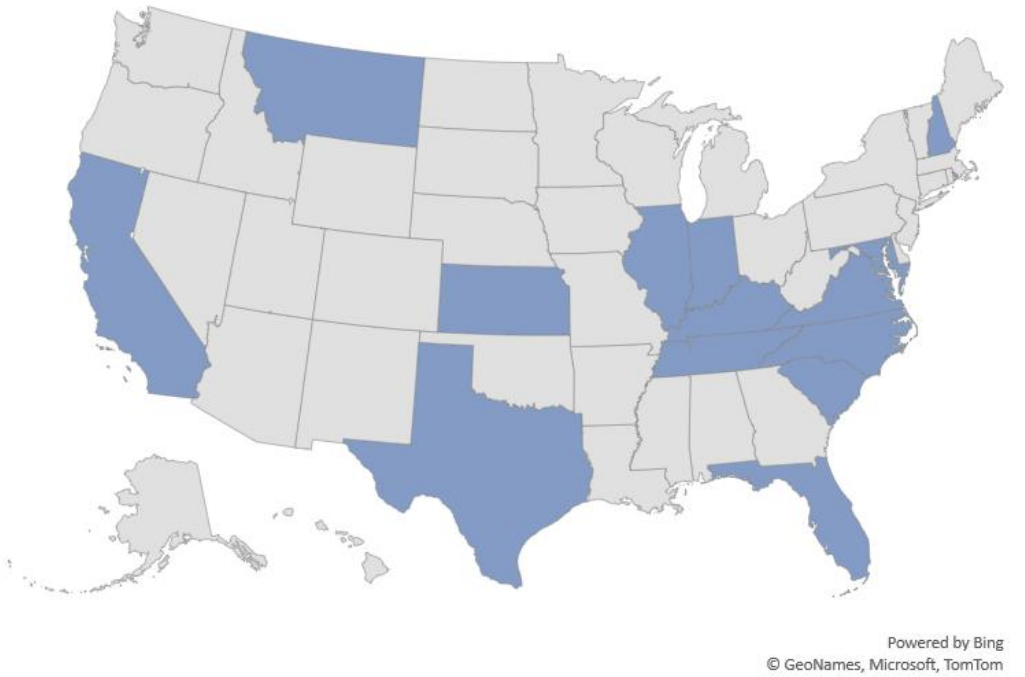


Fig 4: Geographical Range of Participation in NMATE 2019 and 2021

Stakeholders at NMATE 2019 determined the criticality of developing a cohesive and unified strategy for an effective national mutual aid system. They determined that national mutual aid operational needs should drive the policy, which then drives

technology requirements and appropriate information sharing. This sequence, as outlined below, is critical to success.



Fig 5: Proper Sequence for Addressing National Mutual Aid Needs

4.3.1 Progress and Opportunities

Participants in NMATE 2019 and 2021 identified several strengths and opportunities for improvement for resource management and mutual aid operations, policy, and technology. A summary of progress and remaining opportunities are outlined below.

Progress

- In 2021, FEMA released the National Resource Hub—a suite of web-based tools that support a consistent approach for the resource management preparedness process. An updated version was released later that year that included restricted-access APIs and data services to provide resource inventory and personnel qualifications management data to select third-party systems. This is one step in addressing the concern identified in NMATE 2019 that a lack of information sharing forces individuals to work around and outside the system(s), thereby creating inconsistencies that inhibit real-time resource tracking and can result in double-counting of resources, errors, and delays in resource deployment.
- In NMATE 2019, participants recommended that operators identify thresholds that trigger information sharing. Through the identification of a core and simplified set of critical information to inform mutual aid, the resource inventory system within the National Resource Hub has set a precedent for sharing a sustained baseline of information broadly with vetted public safety organizations and staff, thereby negating the need for a trigger for information sharing.
- Participants in NMATE 2019 recommended the creation of a NIMS-related Working Group focused on resource management policy, technology, and interoperability. The NCG Technology Sub-Group and related ad-hoc groups within the NCG have addressed this need.

Opportunities

- A unique identifier schema is needed for resources and personnel across systems to prevent multiple counting of resources and personnel as inventories are integrated. The FEMA Student Identification (SID) number, though not yet required, is being utilized as a unique identifier for personnel

within the personnel qualifications management component of the National Resource Hub, but this continues to be an outstanding need.

- Develop guidance as part of the NIMS program to allow for modified resource requests and typing. This identified need has not been addressed. However, outreach and education continue on resource typing, the ability to discover available resources has improved, and tools to aid in properly typing resources are underway.

5. Next Steps

Progress has been made throughout the duration of this effort by executing the following approach.

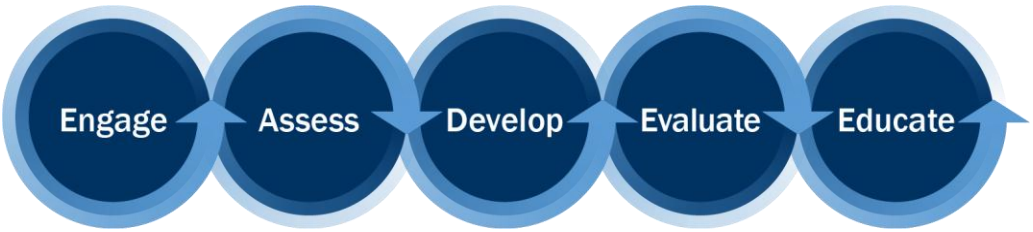


Fig 6: Approach That Enabled Progress

- Engage with stakeholders to ensure requirements for guidance or technology aligns with practitioner needs.
- Assess input to determine themes and implications. Assess available resources and options and determine gaps against practitioner needs.
- Develop solutions to include guidance and technology resources.
- Evaluate solutions with practitioners to determine if solutions address identified needs.
- Educate practitioners about developed solutions.

The following five sections identify recommendations across these areas that, if continued or addressed, would help provide public safety officials and first responders with access to innovative and standardized technology solutions for daily operations that can scale to support large-scale incidents.

Additional recommendations can be found in corresponding reports and products mentioned throughout this document and found in the appendix of resources.

5.1 Engagement

Engagement with the public safety community to ensure that technology and guidance aligns with business practices and addresses practitioner needs is of vital importance.

Recommendation #1: Facilitation of Working Groups | Facilitation of a standing technology group such as the NCG Technology Sub-Group as well as facilitation of ad-

hoc groups (either within the NCG construct or through events like the National Resource Management Summit) as specific needs arise should continue. The scope of membership should be broadened to engage a broader swath of the public safety community.

Recommendation #2: Feedback Mechanisms for Guidance | The complexity by which new guidance, position task books, and resource typing definitions are developed are not well known to the local community. Engagement opportunities should provide an easier and more robust feedback mechanism and leverage common processes such as living documents, distributed collaboration, and automated workflows. This feedback mechanism should be widely advertised to the community to increase engagement. By creating a more iterative process, guidance can become nimble and address emerging threats and hazards.

Recommendation #3: Collection of Best Practices Across All Levels of Government | Avenues to collect local best practices should be further explored. Small, rural, and volunteer organizations are not sufficiently represented on committees who provide input and influence on nationwide guidance. The community would benefit from collaboration amongst federal agencies like FEMA and DHS S&T and NGO partners to promote similar avenues for input.

5.2 Assessment

Frequent assessment mechanisms ensure that new challenges are captured and that progress is tracked.

Recommendation #1: Comprehensive Assessment of Mutual Aid and Crisis Management Systems | A comprehensive assessment of mutual aid and crisis management systems, and information sharing capabilities, should be created and socialized with a nationwide audience. This assessment should focus on all phases (not just planning) and should be independent of any grant or reporting requirements. Coordinating with an initiative such as DHS S&T's System Assessment and Validation for Emergency Responders (SAVER) Program would allow this assessment to capitalize upon current momentum and expertise. This comprehensive assessment should be repeated on a regular basis (e.g., biennially) to account for changes in system development.

Recommendation #2: Scalability and Organizational Nuances | To maximize effectiveness and represent organizations across the country, assessments must explore the nuances between urban and rural, large and small, volunteer and career, and other differences amongst jurisdictions. While resources are often labeled as being targeted to the whole community or SLTT organizations, the varied needs and limitations of this community must be considered during assessments for resources to be useful.

Recommendation #3: Translating Assessments into Action | As needs and gaps are identified through collaborative or individual assessments, they must be translated into action steps for progress to be made in addressing those needs. Developing executable action plans as an outcome of collaborative assessments is vital. Providing

recommended next steps and resources at the conclusion of self-assessments like CARAT and ISAT allow organizations to more readily address their assessment results and further advance their preparedness posture.

5.3 Development

Development includes not only the creation of technology solutions but also guidance, frameworks, and templates. Development work must align with stakeholder requirements to be successful.

Recommendation #1: Guidance Versus Technology | The community indicates that the main challenges in carrying out incident management and mutual aid are not a result of a lack of technology but are due to a lack of overall coordination and guidance. By focusing on guidance and coordination across related efforts nationwide, FEMA, DHS S&T, and NGO partners may gain better traction in the community and further advance mutual aid and national preparedness.

The community must be guided to appropriate resources such as training, standards, and technology based on their needs. Decision charts and workflows can help direct public safety personnel to the correct resources to meet their needs.

Recommendation #2: Interoperability of Federal Systems | Any development on federal or overarching systems should be viewed as prototypes or alternative systems for local jurisdictions. Federal systems should strive to be interoperable with local systems. Systems should strive to complement existing business operations and be as minimally disruptive as possible to operational systems. Removing the duplication of effort (such as inventorying resources in separate preparedness and response systems) will increase adoption rates.

5.4 Evaluation

Evaluations provide the opportunity to determine the ability of resources and systems to meet identified needs and objectives.

Recommendation #1: Ongoing Asynchronous Evaluations | Evaluations should be flexible and asynchronous, allowing greater participation across the community and accommodate individual organizations' pace and schedules. Hybrid models, such as the model used in NMATE 2021, which combined asynchronous work with an in-person, real-time hotwash allowed for in-depth evaluations along with coordination of findings.

Recommendation #2: Evaluation Approaches | Multiple approaches should be taken to evaluate systems beyond the traditional Planning, Organizing, Equipping, Training, and Exercising (POETE) model, to include user acceptance and interoperability testing. Interoperability-focused evaluations, such as those conducted through NMATE, are beneficial to the advancement of resource management and mutual aid and should continue to be hosted.

5.5 Education

Education provides the community with awareness of available resources and equips them with the ability to utilize those resources within their organization.

Recommendation #1: Connecting Resources with Avenues for Outreach | An educational component is needed for every assessment, development, and evaluation resource identified above. Resources such as after-action reports, self-assessment tools, guidance, and technology tools can only provide benefit to the community if they are given awareness of their availability. By connecting these resources with standing avenues for outreach within the public sector and NGO space, broader awareness can be built within the whole community.

Recommendation #2: Distribution of Best Practices and Standards | No individual organization holds all best practices for its domain. Providing a means of sharing innovative solutions can provide organizations with ready insight to tackle common challenges. Organizations at all levels who develop best practices and standards need a venue to share their successes with the community.

6. Key Themes, Questions, and Additional Readings

6.1 Key Themes

- Mutual aid is critical to unified response and addressing the complex nature of emergencies that increasingly cross-jurisdictional boundaries and/or rely on resource assistance as emergency managers and first responders are easily overwhelmed.
- Despite the recognition of the importance of mutual aid, there are challenges with information-sharing and interoperability, innovation, coordination, and capacity building.
- Disaster scenarios are an effective way for end users to understand their needs, priorities, and courses of action for effective mutual aid.
- Extreme, compound flooding event provides an optimal use case due to its whole-of community impacts across governmental, non-governmental, private industry and other civil sectors.

6.2 Questions

- How would you explain mutual aid in an emergency context? What are key terms and stakeholders?
- How do mutual aid agreements relate to technology capabilities and needs?
- What are the most prevalent challenges related to mutual aid effectiveness?
- What mutual aid resources may be required during a flood disaster?

6.3 Additional Readings and Resources

Resources are provided in the order in which they appear in the document.

6.3.1 Providing Benchmarks of Information Sharing Capabilities, Resource Management Systems, and Mutual Aid Processes

- Resource Management Maturity Study Report, https://arcg.is/oTzC5K
- Information Sharing Assessment Tool, https://www.napsgfoundation.org/isat/
- Interoperability Continuum: A tool for improving emergency response communications and

- Interoperability, https://www.cisa.gov/sites/default/files/publications/21_0615_cisa_safecom_interoperability_continuum_brochure_final.pdf
- Capability and Readiness Assessment Tool, https://www.napsgfoundation.org/carat/
- Technology-Related Roles within NIMS Structures Study Report, https://arcg.is/DvW8q

6.3.2 Identifying Information Sharing Standards

- Job Aid: Incident Management Technology – Guidance on Technology Standards, Interoperability, and Acquisition (Interactive Web-Based Version), https://arcg.is/TeKnC
- Job Aid: Incident Management Technology – Guidance on Technology Standards, Interoperability, and Acquisition (PDF Version), https://www.napsgfoundation.org/wp-content/uploads/2021/11/JobAid_Incident_Mgmt_Technology-v3-Final.pdf
- Technical Guide: Incident Management Technology – Guidance on Incident Management Information Sharing Standards (PDF Version), https://www.napsgfoundation.org/wp-content/uploads/2021/11/Technical_Guide_InfoSharingStandards-v3-Final.pdf

6.3.3 Providing Planning Tools

- Resource Management Planning Tool, https://rmpt.napsgfoundation.org/
- Resource Management Planning Tool Description and Overview, https://www.napsgfoundation.org/resources/rmpt/
- Resource Management Planning Tool Developer Toolkit, https://github.com/NAPSG/RMPT-Developer-Toolkit
- Guidance on Risk, Resilience, and Vulnerability Indices, https://www.napsgfoundation.org/resources/indices-guidance/
- One-Pager on the Guidance on Risk, Resilience, and Vulnerability Indices, https://www.napsgfoundation.org/wp-content/uploads/2020/11/Indices-Guidance-One-Pager.pdf
- National Resource Hub, https://preptoolkit.fema.gov/web/national-resource-hub

6.3.4 National Resource Management Summit

- 2019 National Resource Management Summit: Summary of Findings and Action Plan, https://napsg.maps.arcgis.com/sharing/rest/content/items/7ffaf17c8a744ba38460edf589514d66/data
- 2021 National Resource Management Summit: Key Findings and Action Plan, https://www.napsgfoundation.org/wp-content/uploads/2021/10/2021-NRMS-Findings-and-Action-Plan.pdf

6.3.5 National Mutual Aid Technology Exercise

- 2019 National Mutual Aid Technology Exercise Mutual Aid Interoperability Action Plan, https://www.napsgfoundation.org/wp-content/uploads/2019/10/NMATE_Action_Plan_20191018.pdf
- National Mutual Aid Technology Exercise 2019 Summary of Findings, https://www.napsgfoundation.org/wp-content/uploads/2019/10/NMATE_Findings_Summary_20191018.pdf
- 2021 National Mutual Aid Technology Exercise: After-Action Report, https://www.napsgfoundation.org/wp-content/uploads/2022/01/2021-NMATE-AAR.pdf

6.3.6 PrepTech Talks

- Get Smart on Information-Sharing Standards for Crisis Management, https://www.napsgfoundation.org/resources/info-sharing-standards/
- Intelligence-Driven Resource Management & Mutual Aid Planning, https://www.napsgfoundation.org/resources/preptech-talk-intelligence-driven-resource-management-mutual-aid-planning/
- Decrypting Risk, Resilience, Social Vulnerability Data & Indices, https://www.napsgfoundation.org/resources/decrypting-risk-resilience-social-vulnerability-data-indices/
- Innovations in Resource Management & Mutual Aid Technology, https://www.napsgfoundation.org/resources/innovations-in-resource-management-mutual-aid-technology/
- NAPSG Foundation: Delivering Solutions Today, Innovating for Tomorrow, https://www.napsgfoundation.org/resources/delivering-solutions-today-innovating-for-tomorrow/

National Flood Preparedness Guidelines for First Responders

Kevin Kay and Jared Doke[7]

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Abstract:

The public safety community is overwhelmed with emerging technology and data. This tends to result in a lack of interoperability and difficulty in identifying core information needs, policies and procedures, and technology integration with preparedness activities and operations. The Technology Innovation for Preparedness and Response Project sought to accelerate the use and adoption of geospatial tools and datasets through testing and validation with public safety stakeholders, resulting in multiple geospatial solutions, best practices, national guidelines, and a robust training and documentation system to replicate the results across the country. Partnering with two pilot locations (South Carolina and the Colorado North Central All-Hazards Region), NAPSG Foundation and other subject matter experts in flood preparedness and response conducted in-person gap identification workshops, virtual tabletop exercises, working group meetings, and ongoing training opportunities in no-fault sandboxes to prioritize and develop geospatial solutions for the public safety community. These solutions were then tested during real world incidents since 2019 to include Hurricane's Ida and Laura, the Surfside Building Collapse, the Tri-State tornado outbreak, and the recent Kentucky flooding. This effort reinforces the importance of utilizing geospatial tools and technology and demonstrated the value of rapidly prototyping solutions identified by the public safety community. However, the project also uncovered a general lack of adoption of geospatial tools and datasets based on budgets and expertise, and a complicated ecosystem of costly and customized solutions that prevent jurisdictions from being interoperable.

Keywords:

First Responders, Flood Preparedness, core operational information

1. Introduction

"It wasn't raining when Noah built the Ark" (Ruff, 1924).[8]

"911, what is your emergency?" This simple question is asked countless times daily

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[8] This quote was first cited in print in 1924 when it appeared in a newspaper advertisement from Howard Ruff. 19 June 1924, Emporia (KS) *Daily Gazette*, pg. 10, col. 7 ad: It has also been attributed to Richard Cushing, an American prelate to the Roman Catholic Church.

by call takers and dispatchers in Public Safety Answering Points (PSAPs) across the nation. It is the first question that leads to a cascading series of operational decisions by our first responders. During the May 2015 floods in Texas, that question was asked in both highly urbanized and rural areas from Houston to Austin. Historic rainfall increased the complexity of the decisions that emergency responders had to make as rain continued to fall over the course of several weeks. Deadly flash flooding, dam failures, and traffic gridlock in many places were just a few of the effects from this historic flooding. The problem public safety officials often face when making difficult decisions is not about data, rather, it is about how data becomes actionable information. Public safety officials need access to timely, relevant, and trusted information that enables informed operational decisions about that call for service.

In 2016, the Core Operational Information Solution Project sought to identify core data needs to satisfy this requirement by defining core operational information requirements, decision points, and the common data needed to support decision-making prior to a flood event for planning and forecasting, and during flood events. Identifying which data sources were necessary, working with local jurisdictions that had been impacted by both coastal and riverine flooding, and operationalizing this information for first responders led to the first version of the National Flood Preparedness Guideline[9], data-sharing groups, and additional materials to aid local jurisdictions. At the end of the project, it was clear that existing flood preparedness planning locally, intrastate, and regionally was neither procedurally sufficient nor consistent in the use of standardized, innovative technologies. In 2019, the Technology Innovation for Flood Preparedness and Response Project[10] allowed the National Alliance for Public Safety GIS (NAPSG) Foundation to partner with stakeholders in South Carolina and Colorado to address these gaps, resulting in the second version of the National Flood Preparedness Guideline[11], standardized templates (both geo-enabled and static), and an expanded database of core information needs.

2. National Flood Preparedness Guideline

The National Flood Preparedness Guideline (NFPG) was developed to help jurisdictions prepare for, respond to, and recover from flood events by better utilizing technology, modeling, and core data needs. The guideline provides a snapshot of available data sources, modeling, and technology and leverages best practices, use cases, and additional resources from the public safety community to show how flood preparedness and response operations continue to evolve. The second version of the NFPG covers Alert and Warning, Resource Management and Coordination, Modeling and Trigger Points, Data Management and Interoperability, and Operationalizing GIS.[12]

[9] NAPSG Foundation, "National Flood Preparedness Guideline 2017"

[10] The Technology Innovation for Flood Preparedness and Operations project leveraged the findings from the Core Operational Information project. Both were funded by the Department of Homeland Security, Science and Technology Directorate under awards HSHQDC-16-C-B0016 and 70RSAT20C00000008, respectively. When referenced in this document, the Technology Innovation Project references findings and materials from both projects.

[11] NAPSG Foundation, "National Flood Preparedness Guideline 2022"

[12] Ibid

The overall objective of the NFPG is to help jurisdictions address the following challenges:

- The overwhelming amount of reliable, timely, and accessible information that leads to information overload,
- The sophistication of flood models, and
- The pace of technological innovation.

The themes within the NFPG were informed by the Technology Innovation Project, in-person and virtual workshops, and feedback from the NAPSG community. The NFPG was developed with and for the public safety community, with contributing stakeholders representing disciplines such as technologists, GIS professionals, flood modeling experts, the private sector, academia, and other subject matter experts in flooding.

2.1 Alert and Warning

The NFPG focused on enriching alerts and warnings through live, continuously updated maps to provide two-way communication platforms with both the public safety community and the public. This also enables geolocation and targeted information and incorporates existing vulnerability and data sources to improve the accuracy and effectiveness of messaging. Key takeaways include:

- Craft messages in advance. This includes messages pre-populated in mass notification systems and IPAWS, and may include pre-designed evacuation zones, messages in multiple languages and formats, and maps and applications easily accessible to the public.
- Follow the EAS and WEA Standardization Checklists[13], including message source, threat or event, location, timing, protective action to take, and expected end of event or update. If possible, indicate whether the recipient of the message has been geotargeted.
- Register with the IPAWS system and take courses from EMI[14] to learn how to integrate it into your operations. Consider how to partner with the NWS to help distribute local alerts and warnings.
- Explore how social media can augment your alerting system and crisis communications during a disaster. Consider it a two-way communication stream and dedicate resources to manage this.
- Use geofencing to better target resources and alerts and work with your GIS staff to do so. Work with your local vendors to ensure they can support geofencing in their software.
- Use existing datasets to enrich your analysis and provide hyper-local alerts and warnings.

2.2 Resource Management and Coordination

First responders who manage resources are challenged with how to improve

[13] FEMA, "IPAWS EAS and WEA Alert Standardizations Checklists"
[14] FEMA, "IS-247.B: Integrated Public Alert and Warning System (IPAWS) for Alert Originators

the processes for identifying, requesting, and sharing their own resources with other departments and jurisdictions. Flash flooding and other no-notice events can exacerbate resource management and coordination challenges, often leading to double counting of resources or creating an environment where the fastest, not the most in need, jurisdictions receive resources. Key takeaways include:

- Review and implement NIMS protocols and procedures for resource documentation and management. Build Mission Ready Packages to fully understand the supporting factors for a resource to sustain it over the duration of an event.
- Strive for interoperability with other industry and discipline-specific systems such as EMAC's MASS[15] resource management system, or by utilizing open standards.
- Utilize the National Resource Hub[16], to include RIS, OneResponder, and the RTLT from FEMA to improve your preparedness posture and provide the community with an awareness of your resources and personnel.
- Design a resource management dashboard to help operationalize your resources in relation to current event data. These dashboards may contain resource and personnel location, availability, and associated attributes like resource costs and points of contact. Resource management dashboards should cover preparedness, response, and recovery efforts.

2.3 Modeling and Trigger Points

Response to flooding events typically includes a four-step process: estimate impacts, identify critical interdependencies, anticipate resource requirements, and provide response assessment. To do this efficiently, subject matter experts with relevant expertise must incorporate rapid hydrology and hydrologic (H&H) modeling. Local jurisdictions may not be able to easily run or ingest model information; however, they should still:

- Understand your flooding risk and the potential impact of floods on your community by using modeling tools like Hazus[17]. Build expertise in these more advanced tools before an event occurs.
- Strive to replace national datasets with locally sourced data. This data is typically more accurate and current and will provide better model outputs.
- Integrate data from models, such as the National Water Model, into GIS

[15] Emergency Management Assistance Compact, "Mutual Aid Support System (MASS)"
[16] FEMA, "National Resource Hub: Unifying Resource Management Nationwide"
[17] FEMA, "Hazus Program"

and operations for more actionable alerts. Learn how the new model can help with alerts for streams near your location and find the point of contact for your area to train and exercise.
- Work with partners (e.g., USGS, NOAA, etc.) to increase local sensor networks. Consider investing in low-cost sensor systems where appropriate to speed up the alerting in critical areas. These sensors can help you identify needed actions in common data "blind-spots" – areas where more formal and expensive sensors do not exist.
- Develop known trigger points of when to act and integrate these trigger points into GIS and other protocols. Work with your staff to transition this knowledge into data that can help "trigger" actions more quickly in the absence of sensors and data.

2.4 Data Management and Interoperability

As the use of modeling, sensors, and the availability of incident-specific information becomes more readily available, there is a need to ensure that the information is trustworthy and includes adequate checks and balances. This can be achieved through data standardization practices, to include accurate metadata and data transparency. Data should also be put through a rigorous quality assurance and quality control process (QA/QC). Unfortunately, data management is often an afterthought. Key findings in the NFPG include:

- When using data feeds from outside providers, refer to the metadata, including timestamps and confidence levels when making critical decisions. Provide the same for your internal, locally sourced data and information products to support critical decisions.
- Utilize standard symbology[18] to bring clarity and mutual understanding across all your applications. When you begin to share information within and among partner organizations, common symbology helps to tell a clear story. A public safety symbology guideline and library are available in the NAPSG Symbol Library.
- Implement rigorous QA/QC practices for geospatial data. This includes regularly maintaining sensor systems to ensure they are operational and testing their integration into decision-making products like maps, applications, and business systems.
- Utilize data sharing best practices and build an information hub to manage and exchange data within your organization and across partner agencies. Common platforms exist that allow you to exchange data in both public and secure ways. Leverage community best practices and solutions where appropriate to allow for the broadest interoperability of

[18] NAPSG, "Symbol Library"

your chosen system.
- Utilize information sharing standards such as those outlined by the Organization for the Advancement of Structured Information Standards (OASIS)[19].

2.5 Operationalizing GIS

During a disaster, operational cadence and the flow of information increase dramatically. Decision makers need filtered and actionable intelligence, not raw data, to make critical decisions. Role-based, mission-focused applications can help with this process; however, there is still a need for a human to synthesize information and convert it into actionable information for decision makers. It is critical to train and test these systems and processes prior to an incident through exercises, followed by an after-action analysis to identify gaps that should be filled prior to future incidents. After utilizing these applications in multiple real-world events, key findings include:

- Create mission-focused applications to provide decision makers critical information. Consider how you transition from massive catch-all applications, which include all your data and tools, into an environment that better serves the end user.
- Targeted applications will help you avoid information overload.
- GIS-based tools can help process information into actionable intelligence, but you still need context to support decision-making.
- Include the use of location-enabled decision support tools into your exercises to test data assumptions, tools and solutions, and how effective they are at helping achieve data-driven decision-making.
- Review your after-action reports (AARs) with an eye toward data needs and perform post-event analysis to determine both data and analytical gaps that can be addressed before the next event.
- Include your GIS/IT staff in exercise design and during AARs.

3. Key Findings

The NFPG provides key takeaways, best practices, and real-world examples of organizations implementing technology for flood preparedness and response. However, key challenges emerged in the ability to collect the needed information in a single location, as well as an easy way to translate technical needs into operational needs. This led to three additional products; the Flood Preparedness Hub, the Core Information Needs Data Sharing Group, and Geospatial Game Plans.

3.1 Flood Preparedness Hub

The Flood Preparedness Hub[20] is a single location that includes applications,

[19] OASIS Open, “Standards”
[20] NAPSG Foundation, “Flood Preparedness Hub”

resources, best practices, and success stories that were part of the Technology Innovation for Flood Preparedness and Operations Project.

3.2 Core Information Needs

Identifying core information needs enables first responders to effectively utilize datasets before, during, and after a disaster. Findings from workshops found that these datasets had to be easily accessible, categorized in multiple ways (e.g., by hazard, by author, by most recent update), and ingested into applications automatically. The All-Hazards Core Information Needs Group[21] does just that and includes over 120 members and 157 authoritative feature layers.

3.3 Geospatial Game Plans

It is not enough to have the data in a single location; this data needs to be operationalized and used in different phases of emergency management. The concept of the geospatial game plan, developed during this project, addresses the disconnect between operational needs and technical solutions. Geospatial game plans can be hazard specific and in multiple formats (e.g., chart, document, website), and should identify team members, core information needs, and operational and technical game plans.[22]

4. Summary

The Flood Apex Program set a foundation for the identification and use of geospatial products to aid in preparedness and response. Two pilot locations provided operational gaps and technical requirements for geospatial technologies. Important takeaways stressed by the public safety community to guide future development and adoption of these technologies include:

- **Including GIS and IT staff throughout the entire process:** GIS and IT staff are often an afterthought when preparing for and responding to flood disasters. Stakeholders stressed the need to include GIS and IT staff early on to ensure that the correct licenses, infrastructure, information sharing systems, and staffing are available to implement the needed geospatial solutions.
- **Train, exercise, and refine:** The success of the applications developed during the Technology Innovation Project was the cycle of training stakeholders, exercising with the tools, and then rapidly refining and implementing requested enhancements. This was accomplished through a robust feedback mechanism and documentation process, a cadre of power-users to test the solutions, and experienced staff who could determine feasibility vs. level of effort for the requested changes.
- **Data is not the problem – synthesizing the data is:** Modern tools and datasets have given first responders access to an unlimited amount of information. Determining key authoritative datasets, balancing information needs during

[21] NAPSG Foundation, "All-Hazards Core Information Needs Group"
[22] NAPSG Foundation, "Geospatial Game Plans"

different phases of a disaster, and looking at available technology within an agency are critical.

- **Building your cadre:** Local jurisdictions expressed frustration with the inability to tap into subject matter experts outside of their geographic areas. By incorporating virtual collaboration systems and open-source libraries (e.g., GitHub), public safety stakeholders can tap into experts across the country (and the world) who have experienced similar incidents and implemented technology successfully.

5. Key Themes, Questions, and Additional Readings

5.1 Key Themes

When discussing flood-focused geospatial products, several key themes emerged including:

- Identifying the correct "customer" for geospatial flood products.
- Balancing information flow with incident requirements.
- Creating a system that provides robust QA/QC on data sources.
- Exploring flood models that match jurisdictional requirements.
- Putting tools into practice every day.

5.2 Discussion Questions

- What flood data do you need for each phase (mitigation, preparedness, response, recovery)?
- What is your current structure for sharing geospatial information (both internal and external)?
- Where do you typically see issues related to flood preparedness and response – the people, the process, or the technology?
- Does your GIS and IT structure provide opportunities for public safety stakeholders to request applications, technology, or support?
- If your organization contracts out flood-related plans (e.g., Hazard Mitigation Plans, Dam Emergency Action Plans), do you have a plan to build capacity internally? This includes understanding and running flood models or deploying flood technology.
- Do you have the ability to conduct asynchronous (virtual or hybrid) planning, training, exercise, or real-incident activities?
- Do you have a list of applications and/or workflows that you wish to implement in the future? Examples include damage assessment, debris management, sheltering, field data collection, or pre-incident planning.

5.3 Additional Readings:

- U.S Department of Homeland Security GeoCONOPS V5 – A strategic starting point for the coordination of Homeland Security and Homeland Defense geospatial activities.

- FEMA Geospatial Resource Center – A single location providing all-hazards content from governmental, private sector, and volunteer agency partners.
- Flood Preparedness Hub – A single location with best practices, solutions, training and exercise opportunities, and guidelines developed under the Technology Innovation for Flood Preparedness and Response project.
- National Flood Preparedness Guideline – The latest version of the NFPG (2022).
- National Flood Preparedness Guideline (archived version) – The first version of the NFPG (2017) that includes a workshop facilitation section.
- All-Hazards Core Information Needs Group – An ArcGIS Online (AGOL) Group with authoritative core information data.
- NAPSG Foundation Symbol Library – A standardized free-to-use symbol library.
- Homeland Security Enterprise (HSE) GeoCONOPS Hub – A hub site with GeoCONOPS resources.
- Geospatial Game Plans – A template for creating your own geospatial game plan and five hazard-specific examples.

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Enabling smarter flood detection and protection with low-cost sensors in North Carolina and Kentucky Communities

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Abstract

Flooding continues to be the United States' most frequent and costliest disasters. One of the key challenges to the flood problem in the United States is the lack of robust sensor networks combined with GIS technology that allow for a more wholistic view of a community's flood risk. Sensors networks have traditionally been deployed along rivers or the coastline, but not in areas more prone to urban flooding or on local dams or levees that may pose a risk of flooding from infrastructure failure. This project sought to better understand community flooding using low-cost IoT flood sensors combined with GIS as a means to improve flood risk reduction, improve public works response to flood emergencies, and increase water infrastructure resilience. It leverages uses cases in the Charlotte, NC metropolitan area and the state of Kentucky, validating emerging low-cost flood sensors technology and provisioning user guides to support their deployment by community risk managers and infrastructure operators.

Keywords:

Low-cost sensors, IOT, flood detection

1. Introduction

"Floods are 'acts of God,' but flood losses are largely acts of man." (White 1945). [25]

It is commonly understood that the impact from flooding has increased over time. Flooding throughout the US is one of the most frequent and damaging natural hazards. The National Weather Service estimates that nearly 30 deaths per year and $7.8B in annual losses can be attributed to flooding. Each year lives are lost, property is

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[25] Gilbert White (1945). *Human Adjustment to Floods.* University of Chicago Department of Geography Research Paper No. 29. Chicago: University of Chicago Department of Geography.

destroyed, and infrastructure is damaged during flood events. In many cases, additional information about the flood hazard would allow landowners and emergency responders to proactively respond and mitigate before the flooding occurs. Knowing where flooding is happening, and where it's likely to happen in hours or days, will save lives and avoid damage.

Imagine life today without smoke detectors or fire suppression systems. "We need smoke detectors in our creeks" a former fire chief leading the swift water rescue team once told staff in Charlotte-Mecklenburg's Storm Water Services. Smoke detectors provide alerts when the hazard is starting before signs of a full fire. Flood sensors at a price point that allows them to be installed throughout communities in areas of greatest need, begin to build a network of smoke detectors throughout watersheds.

In Charlotte-Mecklenburg, NC and critical parts of Kentucky, lower cost sensors were installed in 2017-2019 as part of a research partnership with the Department of Homeland Security Science and Technology Directorate (DHS S&T). Both agencies tested, refined, and experimented with leveraging the sensors with other technologies to provide life saving information. This paper shows the benefits and challenges encountered in these two case studies.

2. Use Case – Charlotte-Mecklenburg, North Carolina

In the late 1990's, Charlotte-Mecklenburg Storm Water Services (CMSWS) revamped its floodplain management program. The changes were aimed at reducing long term flood risk and saving lives. Ultimately CMSWS was looking to make the Charlotte-Mecklenburg area more resilient to the impacts of heavy rain and flooding. A few of the strategies included:

I. a digital floodplain map maintenance program including 'Future Conditions' floodplains and building specific elevation data;

II. an aggressive floodplain buyout program derived from innovative mitigation planning, assessment, and tracking of results; and

III. an automated Flood Information and Notification System (FINS) that functions from real-time field data situated in Charlotte-Mecklenburg's urban flash-flood environment.

Around 2012, CMSWS developed the framework for an innovative building-specific Flood Risk Assessment and Risk Reduction (RARR) Plan. Data driven decision models were built into an automated RARR tool to create a dynamic, continuously updated "plan" that aids in identifying, prioritizing and planning future flood mitigation efforts. The tool utilizes FEMA floodplain map data along with local datasets to assess property level flood risk, evaluate 19 risk reduction techniques to determine effectiveness, and assign community driven prioritization to mitigation actions.

CMSWS created and implemented FINS as part of a strategic initiative to give emergency responders more time to proactively respond to flood prone locations during an event. In an urban environment, 911 calls for help can be the first indication of flooding. This is too late and puts people and property at increased risk. The FINS

network of US Geologic Survey (USGS) gages, in combination with a complex communication and automated notification system, does a large part in providing flood data at a limited number of locations that have USGS gages nearby.

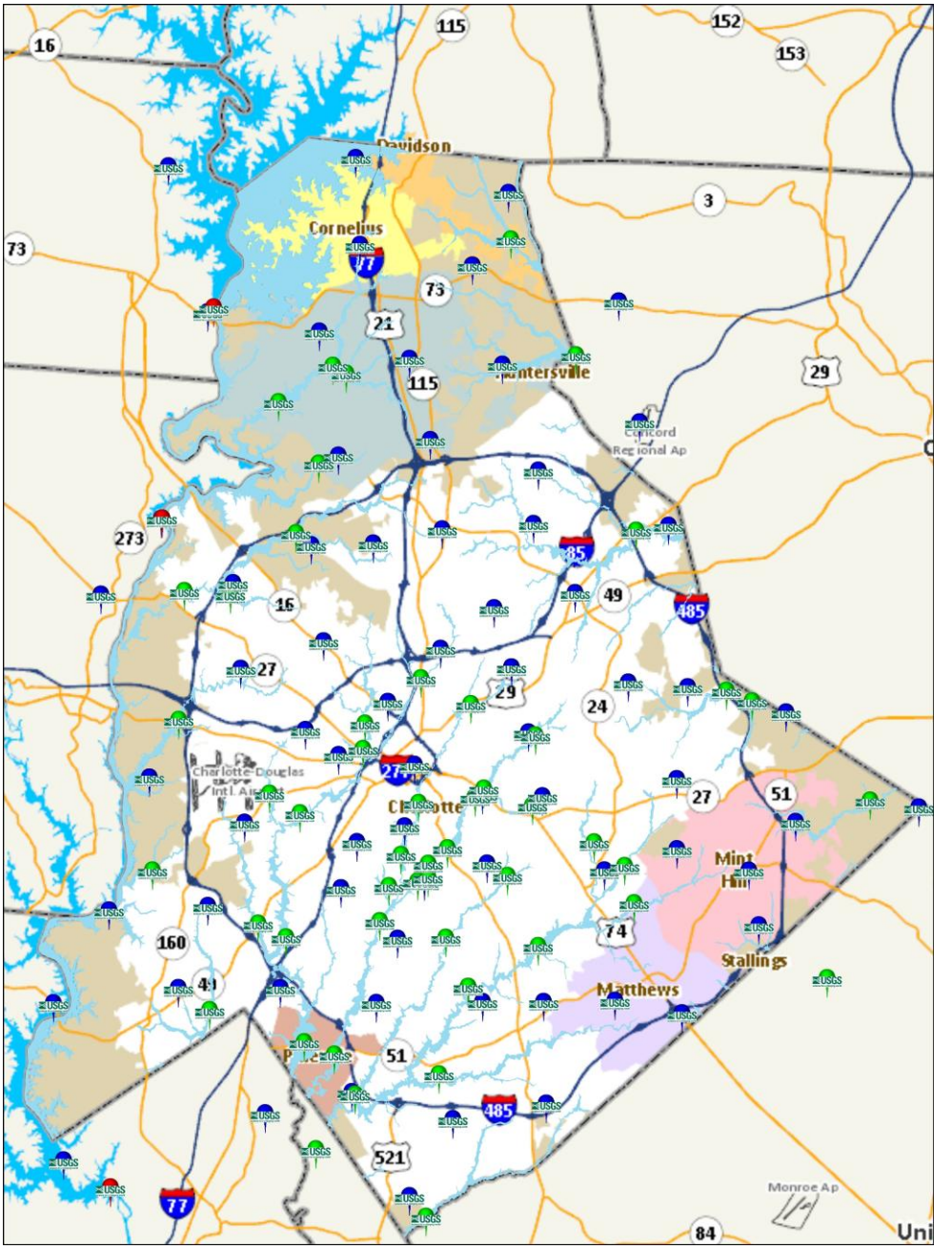


Fig. 1: **FINS USGS Stream Gage Network**

CMSWS has reduced risk in local floodplains by over 40% since 1999. However, there is still work to be done with thousands of builds in the floodplain and dozens of street segments vulnerable to flooding. The FINS network had many geographic gaps in flood prone areas that can result in lack of proactive response. The key to furthering this initiative and advancing it in a more comprehensive way are lower cost flood sensors.

2.1 Initial Flood Sensor Deployment

In 2017, Mecklenburg County had a relatively extensive network of rain and stream gages installed and maintained by the USGS. This consisted of about 40 scientific-grade stage gages used by both Charlotte-Mecklenburg Storm Water Services (CMSWS) and the USGS. The existing Flood Information and Notification System (FINS), developed by CMSWS to provide advance flood notification to Emergency Responders and businesses, uses real time data from the gage network. The system was a great basis to test lower cost flood sensors and explore adding new features for improved flood detection. Deploying new sensors would also allow CSWSW to see how they would integrate into existing systems like FINS as detailed in Figure 2.

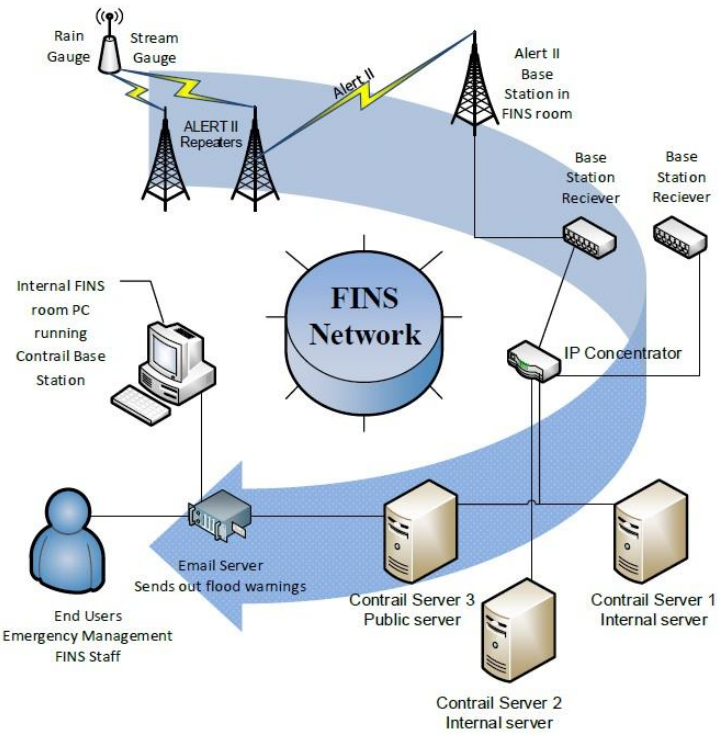


Fig. 2: *FINS Technical Concept*

Charlotte-Mecklenburg has over 350 miles of mapped floodplains that nearly all originate within the County. Therefore, urban flash flooding can occur in one watershed that received intense rainfall, while the one nearby receives little to no rain. This drove the need for CMSWS to explore way to cost-effectively expand the gage network.

In 2018 CMSWS strategically selected 75 'alpha' low-cost flood sensors (LCS) sites for deployment. CMSWS received 25 LCS from 3 vendors to test a variety of technologies. The 75 LCS were deployed to 25 sites split into 5 'mesh' networks of 5 sites each. Each site was configured with a single LCS from each of the 3 vendors. Two of the sites were co-located with a pre-existing USGS stream gage for QA/QC purposes. Installation of the LCS began in July 2018 and were completed in November 2018. Generally, installation of a single vendor's 25 LCS required approximately 5 field days to complete. Units that relied on radio communication proved problematic and 3G and 4G cellular communication was significantly more reliable. Upon installation, most of LCS units performed reasonably, however battery life and communication challenges persisted. These challenges caused each vendor to perform firmware updates. In some cases, hardware was replaced on problematic units in the field.

2.2 Field Deployment Plan

The key to smarter flood detection using more field equipment is to have a strategic deployment plan. The plan should include redundancy where possible and focus on the end results needed for flood detection. CMSWS deployment plan was prepared to significantly increase flood sensor coverage in high risk areas and test the LCS's performance under a variety of urban conditions and settings. Sites were identified through a GIS based tiered selection methodology that focused upon monitoring the most flood prone areas. The methodology scored sites in the following 7 categories:

1. Unmonitored flood risk. The existing FINS network monitors much of the existing flood prone areas of Mecklenburg County. The LCS deployment identified 35 additional sites to augment the existing network.
2. Stream Crossings. Placement of 10 LCS at flood prone road crossings will provide additional information on overtopped roads and sites of frequent debris blockages.
3. Critical Infrastructure. Significant infrastructure assets are in flood prone areas. These assets include lift stations and high hazard dams and previous mitigation sites. A total of 30 LCS have been allocated to this category.
4. Existing Capital Improvement Project (CIP) Sites. 14 sensors were allocated to monitor newly constructed CIP sites and know future sites.
5. Rapid Deployment. A pool of 5 sensors will be maintained in the lab and deployed in advance of significant events.
6. USGS Validation. 3 LCS will be installed in parallel with existing USGS sites to test he accuracy and reporting capability of the LCS.

7. Public Demonstration Site. One LCS sensor will be installed at a flood prone area with significant public access and use to inform the public about the project and direct them to a website where they can learn more about the project.

2.2.1 Sensor Deployment Techniques

CMSWS installed all 75 sensors as part of a contract the Department of Homeland Security Science & Technology Directorate (DHS S&T). Field conditions are harsh on equipment. CMSWS was able to refine materials lists and installation techniques from the experience to ally to beta and commercial versions of sensors.

Rapid deployment can be highly beneficial for flood detection in situations where flooding is predictable or prolonged. CMSWS setup 5 LCS as "Rapid Deployment" platforms. The ability of these flood sensors to be rapidly deployed and provide usable data will be an additional benefit to FINS and First responders. Rapid Deployment units were tested and used in circumstances where weather forecasts predict a significant event with at least 24 hours' notice and where temporary flood monitoring was needed. The Rapid Deployment units were not utilized in flash flooding situations where staff safety could not be assured when deploying the units.

Quick and flexible setup configurations of sensors is important to their value for rapid deployment. Field technicians figured out how to quickly mount the pressure sensor and the communications unit to a variety of objects as needed. Permanent installation units are mounted to 2" posts (Figure 3), pedestrian bridge railings (Figure 4), fencing t-posts, and 2" pedestrian railings at the top of a culvert. The inherent flexibility of the LCS units allow users to easily adapt to a variety of situations in the context of rapid deployment. For ease of installation and the ability to re-use hardware, fencing t-post was used to secure the communication units when a permanent structure was not available. Pressure sensors were secured to aluminum angle brackets fabricated by CMSWS with stainless steel ¼" hardware (Figure 6). The angle brackets were secured with a stainless-steel U-bolt to a piece of rebar that is driven into the streambed or ground at the monitoring site. When beta versions of the sensors were deployed, CMSWS used rebar in lieu of t-posts to prevent the build-up of debris during and after storm events. Rebar can be driven below stream baseflow elevation to reduce debris accumulation. When positioning the units on site, consideration of the maximum solar exposure should be a priority along with mounting the head unity above typical flood levels.



Fig. 3: *LCS communication unit mounted to a 2" galvanized fence post.*



Fig. 4: *LCS communication unit mounted to a pedestrian bridge railing.*



Fig. 5: *LCS in-stream sensor mounted to aluminum angle bracket.*

Long-term installation must handle the rigors of moving water to be reliable for flood detection. When the sensors are installed in a long-term monitoring situation, 2" galvanized fence posts were used to mount the communication units above the 100-year flood-plain elevation in a location where the tree canopy does not interfere with solar exposure. Conduit was utilized to help protect the wire during a long-term deployment. Threats to the wire include routine landscaping, floating debris during high water conditions, and damage from chewing animals. The lower pressure sensors were installed using the same techniques as described in the rapid-deployment installation. This includes the aluminum angle bracket and a stainless-steel U-bolt to attach it to a piece of rebar driven in the streambed or flood plain.

2.3 Flood Threat Notifications

FINS relies on automated notification to staff, Charlotte Fire dispatch, and other specific stakeholders. After about 6-months of successful installation, testing, and data verification, CMSWS began to determine site-specific flood warning thresholds. Using detailed GIS data layers, predicted flood elevations and infrastructure data, CMSWS identified all property, people or structures in the general area of each sensor that are at risk of being impacted by flood waters. Once the flood threats are identified, CMSWS used GIS data layers to determine the mean sea level (MSL) elevation for each of the

structures. Based on data for each site, CMSWS created three levels of flood notification for sensors located in areas having a high risk of flooding. This is the existing protocol used with the USGS gages in the original FINS network.

- "Alert" level – this level of warning is intended to make the target groups aware that a flood event is possible.
- "Investigate" level – this level of warning is intended to make the target groups aware that a flood event has been identified and appropriate action needs to be taken.
- "Emergency" level – this level of warning is intended to make the target groups aware that a flood event is occurring and structures near the flood sensor are being impacted.

For rapid deployment notifications, the installation team documented the location of the LCS, as well as the closest physical structure (such as a road, home, greenway, etc.). Staff then used LIDAR elevation data to assign a MSL elevation to the LCS and the nearby structure(s). These MSL elevations were adequate for quickly creating all three levels of flood warning alarms in FINS.

Notifications were communicated to the target groups based on refined protocols from the existing FINS system and include the following:

- Email or a text message. Emails and text messages will be generated automatically from a CMSWS FINS server where flood warning rules have been created to respond to LCS data.
- Wireless Emergency Alerts (WEAs). WEAs go directly to any smart mobile device near the flood sensor that detected the flood threat. WEAs technology does not require a receiving smart mobile device to have a data package subscription.

Target groups interested in early flood detection in Charlotte are listed in Table 1 below.

Table 1: Target Groups and associated Communication Methods

Target Group	How are members of the group identified	What are communication methods to be employed
First responders	CMSWS public liaison will contact all local emergency responders and request they submit all email addresses and mobile numbers for first responders.	Email address and mobile numbers will be grouped together, so all members of this target group will receive the same flood warning message simultaneously.
Citizens at immediate risk of flooding	First responders dispatched to the area experiencing flooding conditions will notify this target	Physically going door to door of homes and business. Placing barricades on flooded roads

	group.	or send WEA to all active smart mobile devices in the area.
Emergency Operations Center Staff	EOC staff will be anyone checked-in at the EOC during an emergency event.	Two-way radios, face to face interaction, email address and mobile numbers are grouped together, so all members of this target group will receive the same flood warning message simultaneously.
News Media and Social Media	CMSWS public liaison will reach out to all News and Social media groups that have coverage in the areas where LCS are installed.	Email addresses will be grouped together, so all members of this target group will receive the same flood warning message simultaneously. Messages for Social Media groups will automatically be posted to appropriate app or website.

2.4 Operations and Maintenance

Operation and maintenance activities are critical to the long-term durability of any piece of field equipment. CMSWS staff initially performed routine inspections (once every 3 weeks) of the equipment. Although inspections don't need to be this frequent normally, increased frequency should be considered during seasonal insect activity, vegetation growth and severe storms. Until installations were refined, there was need to remove large amounts of debris that collected on the units during rain events. The removal of this debris from around the in-stream t-post was the most labor-intensive maintenance requirement. Once CMSWS installed the in-stream equipment with rebar, maintenance was reduced. Site visits by a field technicians occurred after rainfall events ≥1" rainfall depth to assess and document the condition of the sensor and installation. The following items were reviewed during site visits:

- Removal of any debris collected by the in-stream sensor mounting platform
- A validation water level measurement will be collected
- Check the security of all components and adjust as needed
- Record all information in maintenance activity software/database

2.5 Performance Analysis

The LCS tested by CMSWS present an extremely useful tool for storm water programs of all sizes. They are relatively simple to install and operate but require an active maintenance program similar to other field equipment. They are highly versatile and can be permanently installed in a variety of settings including wet and dry sites or rapidly deployed in advance of storms at high-risk areas. The LCS do not take the place

of USGS gages and do not provide the same level of scientific accuracy or data. However, they can be quickly deployed almost anywhere a community needs reasonably accurate real-time flood data to warn citizens and first responders and support decision making.

During the testing phase, two of the LCS sites were co-located with an existing USGS stream gage for QA/QC purposes. In general, the LCS performed as intended after the firmware updates. The accuracy of the units was approximately equivalent to the manufacturer specifications of 0.04 feet, which was determined through comparison with co-located USGS gages and field verification measurements during baseflow. After the firmware updates, the units transmitted data for approximately 90% of the testing period. Lapses in transmission were attributed to low battery voltage, damaged equipment, and vandalism. Approximately 22% of the LCS units experienced equipment damage that resulted in lapses in data transmission. Most of the damage was to the in-stream sensors and head units. Causes of the damage were in-stream debris, fallen trees and vandalism.

Problems were encountered with the ability of the integrated solar array to effectively charge the units during periods of extended cloud cover (>72 hours) and at sites with dense tree canopy. The accuracy of the LCS units was excellent and met the needs of all use-cases monitored by CMSWS. An active and ongoing operation and maintenance program has been essential to successful operation of LCS.

While conducting the routine maintenance on the LCS, CMSWS staff collected validation measurements of the water level above the LCS. The measurements were generally collected during baseflow conditions and do not represent flooding conditions. However, the USGS comparisons show that these sensors perform well during these higher stage events. Statistical comparison of the difference between the recorded stage and the measured stage was performed and is presented in Figures 7 & 8. The median difference for the validated measurement for all sites was 0.035', which is nearly equivalent to the 0.04' of accuracy reported by the manufacturer. The validated measurement was calculated from the LCS sensors that were operational during the evaluation period.

The residual differences among the LCS sites during the evaluation period is summarized.

Minimum (Ft)	1st Quartile (Ft)	Median (Ft)	Mean (Ft)	3rd Quartile (Ft)	Maximum (Ft)
-0.4658	-0.0033	0.0350	0.0497	0.0933	0.6800

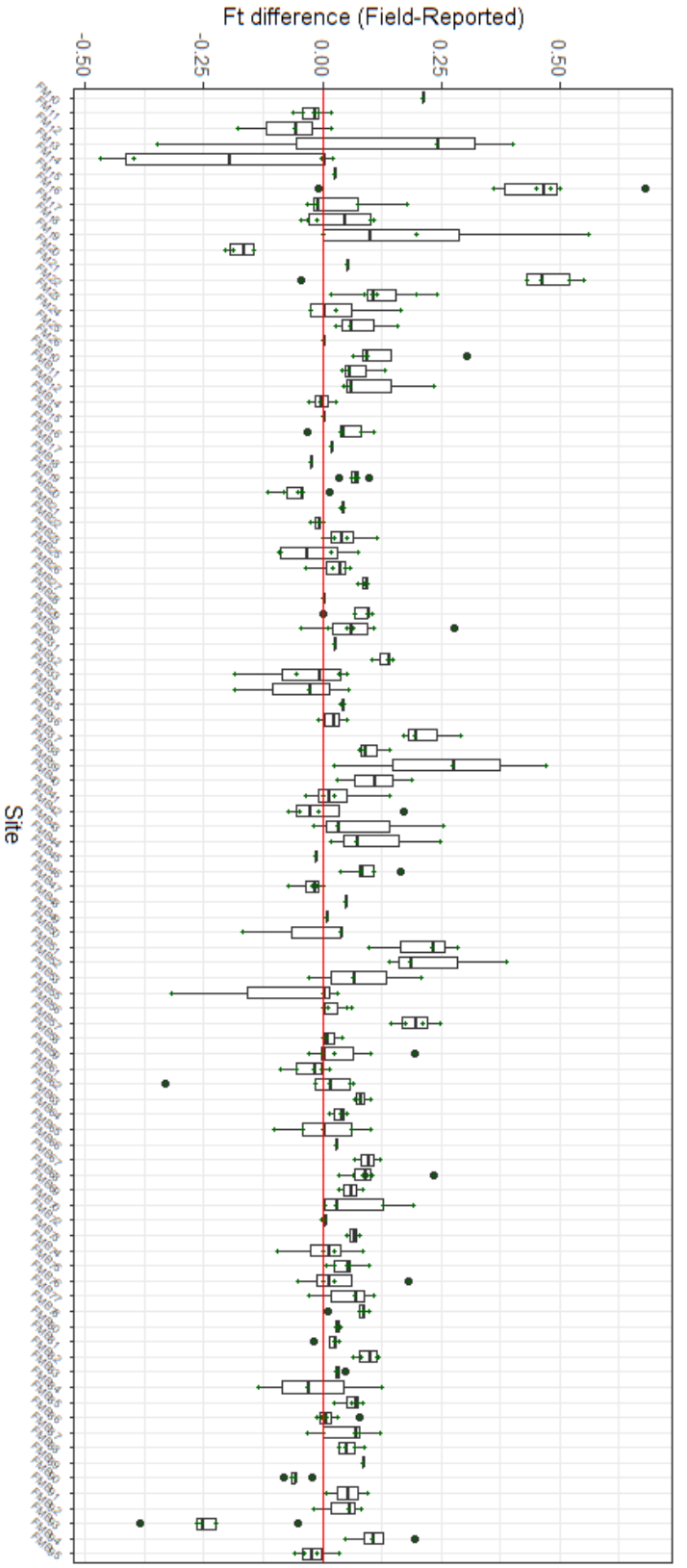


Fig. 6: *Boxplot analysis for each site's residual difference between the measured and recorded values during the evaluation period.*

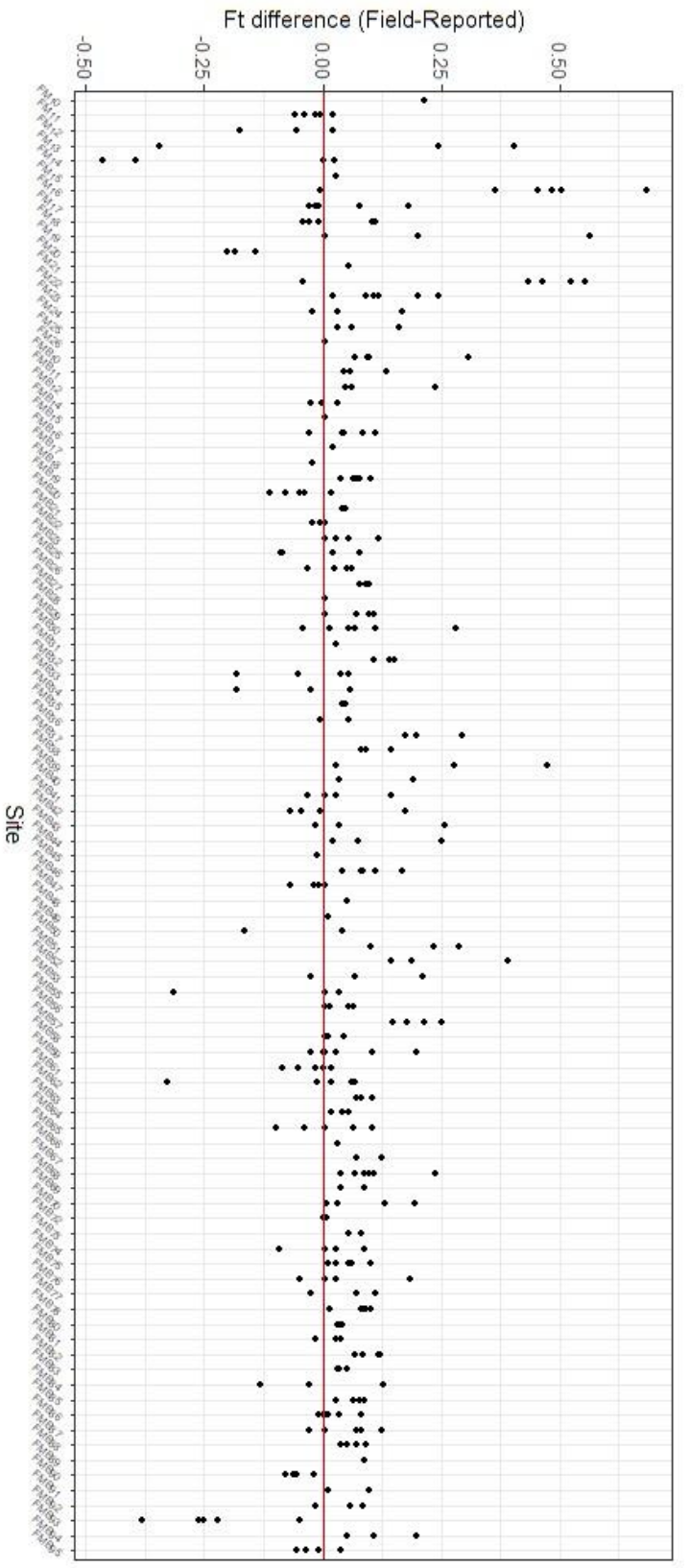


Fig. 7: *Plot of residual values for each site when comparing the measured and recorded values during the evaluation period.*

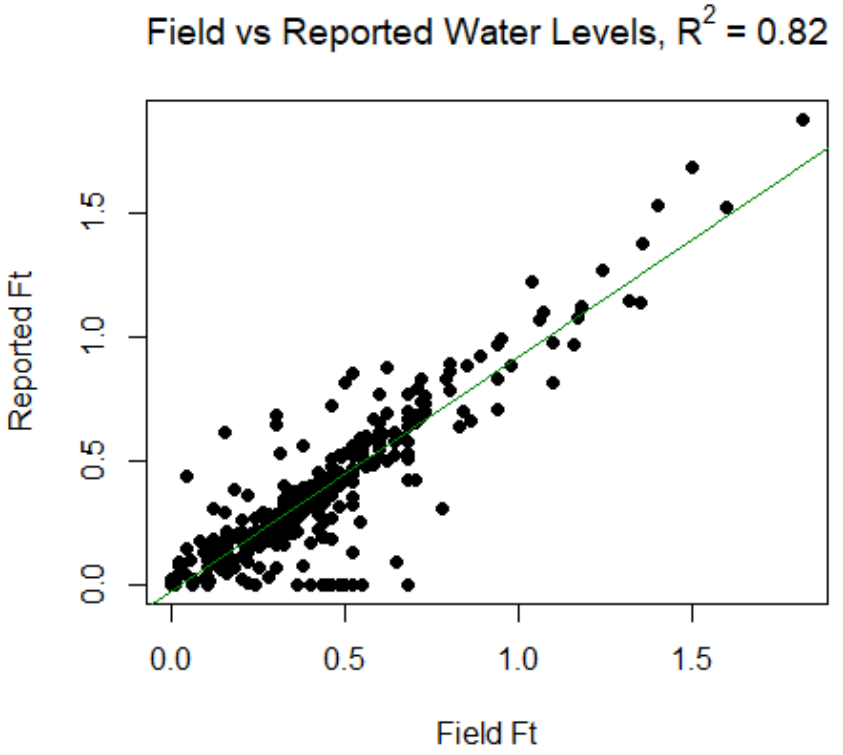


Fig. 8: *Plot of reported stage heights versus field measured heights with the corresponding R2 value.*

The accuracy of the LCS exceeded the expectations of CMSWS. The accuracy of the LCS did not appear to diminish over the testing period and validation measurements were consistently within expected tolerance. Although not as accurate as a USGS gage, the LCS provided a more than adequate level of accuracy for general flood monitoring and the generation of flood warnings.

One of the needed functions of the LCS in an urban flash flooding environment is to support the generation of warnings and alerts to inform emergency responders of flood conditions endangering life and property. CMSWS integrated the LCS into the existing FINS system to expand the waring and alert capabilities to additional sites. Testing of the warning and alert capabilities of the LCS data was highly successful.

Overall, the beta LCS units performed effectively in Mecklenburg County. This is largely the result of an active operation and maintenance program to monitor the performance of the sensors, collect validation measurements, maintain site conditions and repair any damage encountered. It is critical that any community using LCS implement a comprehensive operation and maintenance program to ensure the

equipment is functional when needed during emergencies.

2.6 Automation and Display Summary

The final phase of work related to visual real time displays that would allow visuals of flood inundation and summary of impacts. CMSWS developed a dashboard using data from the LCS and flood risk datasets to communicate real time flood risk. These inundation mapping tools utilized LCS and USGS stream gage data to produce near real time representations of flooding via. The tools utilized a probabilistic approach that leveraged existing flood model output, cross section data and GIS processing to produce flood inundation maps. The maps can be used during flood events to provide event intelligence to first responders. The inundation mapping tools were also integrated with existing elevation certificate, flood risk and mitigated structures data to provide rapid post event damage assessments and losses avoided estimates.

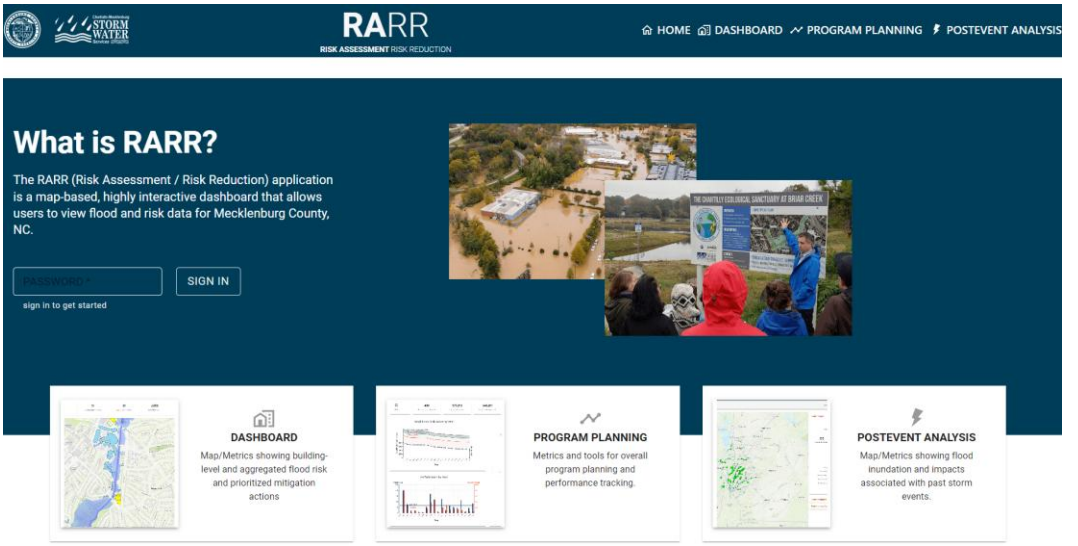


Fig. 9: *Dashboard of "real time" risk tools*

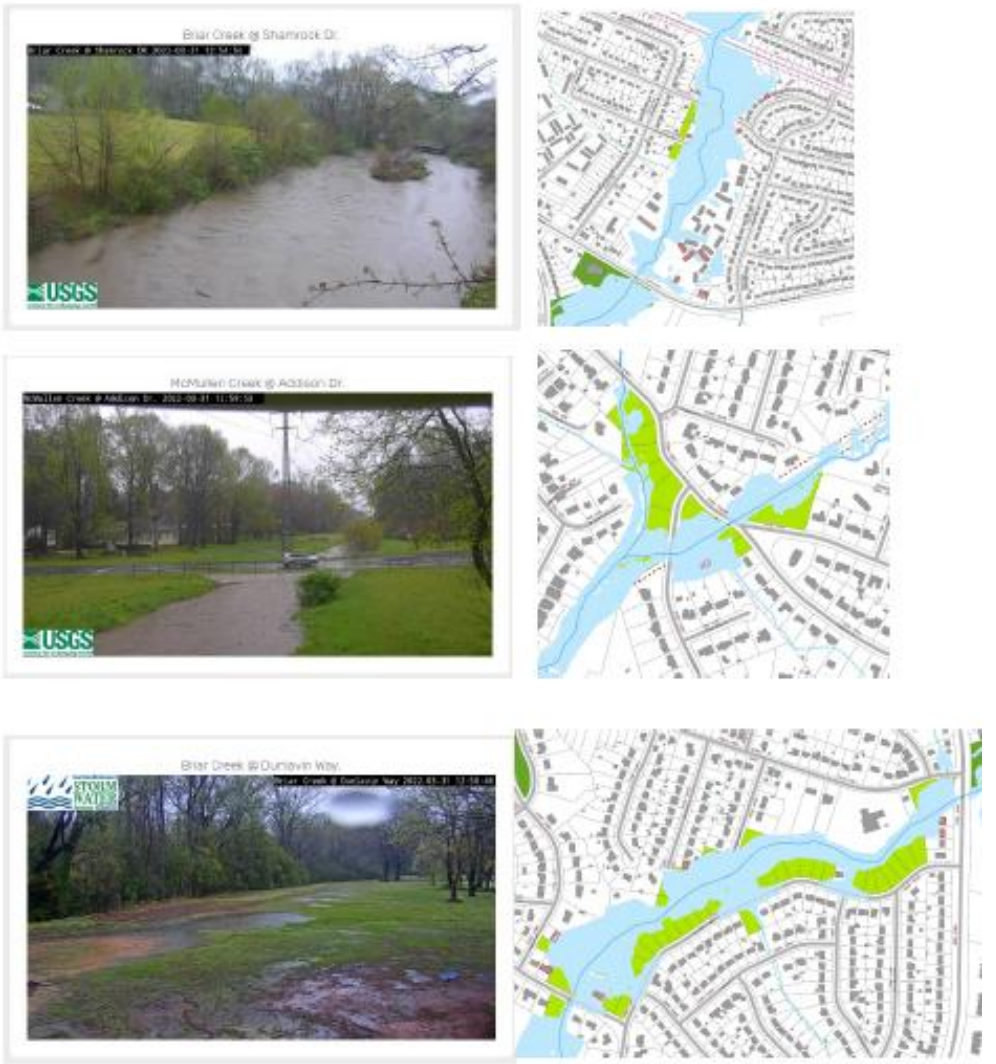


Fig. 10: *Actual event showing inundation boundary*

3. Use Case - Kentucky

The Kentucky Division of Water (DOW), in cooperation with the Department of Homeland Security Science and Technology Directorate (DHS S&T), was awarded a phased project to monitor critical infrastructure, particularly dams, as part of the DHS S&T Flood Apex Program. The overall project identified appropriate methods to assess dam-related failure modes, available technology to develop warning thresholds for dam-related incidents, and deployment of water level sensors to serve as a replicable, cost-effective, and efficient solution that can be applied to critical infrastructure.

DOW tested and installed an extensive number of water level sensors at high and significant hazard dams, many of which are remotely located and have little or no existing instrumentation. These allowed DOW to assess dam-related warning needs in critical areas of the Commonwealth in order to develop prototype warning thresholds that will ultimately lead to enhanced warning for dam owners, emergency management professionals, and other related stakeholders to better prepare for and mitigate dam-related incidents. In the future, DOW plans to extend implementation to differing use cases including levees, low water crossings, and municipal stormwater applications to address pluvial flooding.

As a result of utilizing sensors from multiple vendors, DOW has identified the need for a centralized data management platform. This will provide a single user interface to organize large amounts of data from multiple sensor vendors to streamline communication of dam-related hazards, namely floods, in warning and alert delivery. This statewide monitoring program intends to increase warning and response time in order to reduce risks to lives and property and ultimately build community resilience to flood events of all types, including dam inundation.

The project included installation of Internet of Things (IoT) flood sensors provided through a DHS S&T research grant to monitor pool elevations, a commercially available low- pressure transducer to monitor pool elevations and to serve as a control for IoT sensors, flow monitors in toe drains to monitor internal erosion, and a drone equipped to collect survey data and imaging of the dam to monitor for seepage and movement of the dam over time.

The prototype dam breach warning system includes development of a single dashboard that allows users to view current and historical water levels at the monitored dams in Kentucky. In addition, the system will provide users a subscription service to alerts when water levels reach a certain threshold or when water level changes that surpass a given rate are detected.

The remaining phases of this project included development of the instrumentation into a prototype dam incident warning system, operation and performance evaluation, and dissemination of best practices. Means of dissemination included internal communication within DOW, Kentucky Association of Mitigation Managers (KAMM) and US Army Corps of Engineers Silver Jackets, among others. The best practices will be applied to other dam locations in the Commonwealth that have limited information and/or instrumentation. These tools are intended to increase warning and response time, ultimately reducing risks to lives, infrastructure and property.

3.1 Phase 1: Site Pilot

The first phase of the use case involved the analysis and selection of the initial dams to be used for testing. Utilizing the criteria defined below, dams were evaluated and a selection of dams that were ideal for the initial round of testing were identified.

3.1.1 Site Selection

Fourteen high-hazard dams were selected as potential pilot sites for further evaluation based on knowledge of the dam inventory and dam risks. These potential

pilot sites represented a mix of ownership (both state and local), and construction type (earth fill and rockfill), and were within 1.5 hours of travel from Lexington/Frankfort. The sites were ranked by evaluating for:

- Travel Time
- Failure Risk
- Population at Risk
- Existing Instrumentation / Available Data

The intent was to select a pilot site where pertinent information was already available to limit the amount of data collection required to identify and monitor for potential failure modes. Information about the dams was collected and the sites were ranked based on this information as shown in Table 1. This table shows the dams that were evaluated, and the criteria used to evaluate these dams. Four dams were selected from this list for initial testing, leading to the selection of the following four sites using multiple criteria which are shown in figure 11:

Freeman Lake / Valley Creek MPS No. 4, Hardin County

- Existing instrumentation (piezometers) that is routinely read and reported
- Recent re-construction (2000) with as-built and geotechnical information available
- Annual inspection records available
- Good working relationship between owner (City of Elizabethtown) and DOW

Guist Creek Lake Dam, Shelby County

- Existing instrumentation is no longer working
- Proximity to Lexington and Frankfort
- Significant maintenance issues that require regular surveillance
- State owned dam

Clements Lake Dam, Rowan County

- Immediately upstream of Morehead State University, high downstream population at risk, warning time is less than a minute
- Significant maintenance issues that require regular surveillance
- State owned dam

Willisburg Lake Dam, Washington County

- Large amount of construction and design information available, geotechnical subsurface investigation report available
- Significant maintenance issues that require regular surveillance
- State-owned dam

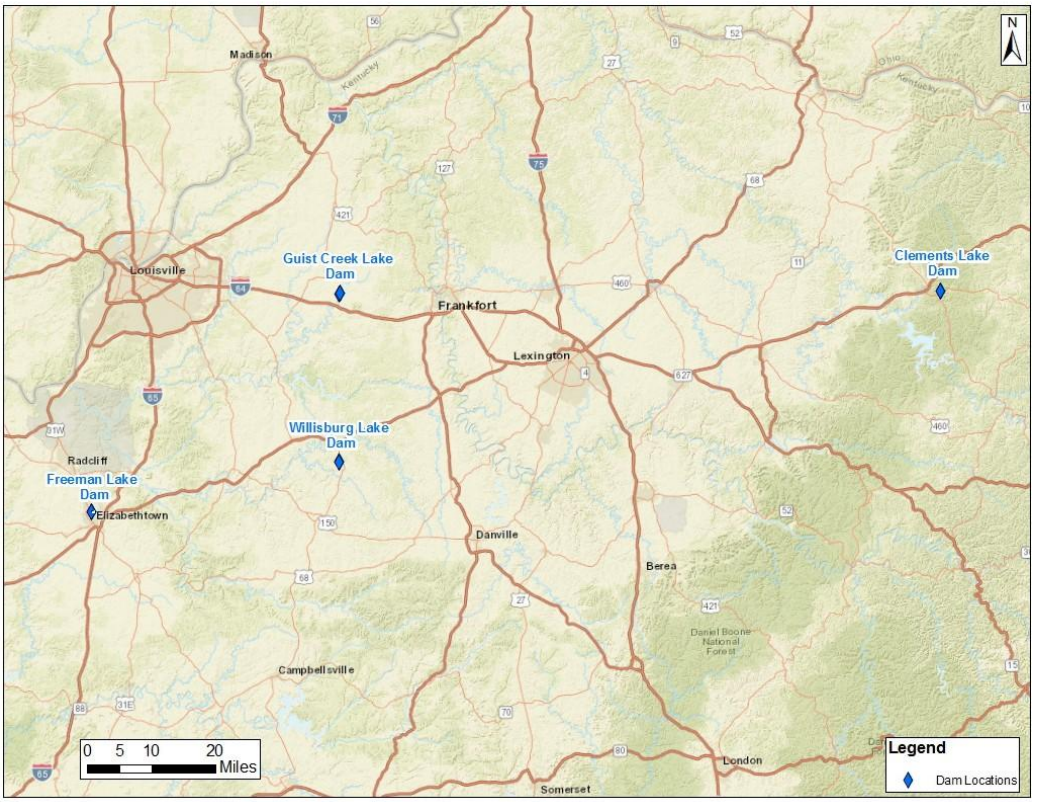


Fig. 11: *Kentucky Pilot Sites*

3.2 Risk Evaluation

Potential failure modes at four pilot sites on dams were reviewed. The intent was to identify general failure modes (applicable to most earthen dams) and develop a strategy to monitor for the failure modes, but not to perform a detailed potential failure mode analysis (PFMA). The following failure modes were noted. These are listed in order of perceived likelihood of occurrence based on experience and history with dams in Kentucky:

- Internal Erosion/Piping
- Overtopping
    - Erosion/Headcutting in the Emergency Spillway
    - Dam Crest Overtopping
- Slope Instability
    - Static
    - Seismic
    - Rapid Drawdown
- Other
    - Sinkhole Formation
    - Maintenance Issues
    - Terrorism/Vandalism

3.3 Instrumentation

After the failure modes were identified, available instrumentation to monitor for the potential failure modes was evaluated. Instrumentation reviewed included:

- Seepage Weirs
- Flow Monitors
- Soil Extensometers
- Vibrating Wire Piezometers
- In-Place Slope Inclinometers
- Low-Pressure Transducers
- Internet of Things (IoT) Flood Sensors
- Fiber Optic Sensing
- Drones
- Non-contact Water Level Sensors

A description of each type of instrumentation is summarized in Appendix D.

3.3.1 Instrumentation Selection

Criteria was developed to review the instrumentation and aid in selection of appropriate instrumentation. These criteria are listed and described below.

- Ability to monitor multiple failure modes – instrumentation that can monitor more than one failure mode was prioritized over instrumentation that only monitors one failure mode.
- Cost (purchase and Installation) – the overall cost of the instrumentation was estimated to determine its cost-effectiveness. Furthermore, cost of data service was included in cost determination
- Difficulty of installation – This was subjective and judged as low, medium, or high. Installation difficulty looked procedures including number of cable connections, mounting hardware, ability to attached pressure transducer underwater, and software setup.
- Difficulty of Automation – This was subjective and judged as low, medium, or high. Based on the vendors' provided dashboard for monitoring their sensors, how difficult was it to set up notifications and automation for sensor alerts.
- Required Maintenance – This was subjective and judged as low, medium, or high. How much routine maintenance was required, such as resetting system, replacing parts, cleaning, etc.
- Applicability to Kentucky State-Owned Dams – if successful, implementation of the instrumentation can be rolled out to other dams within the state's inventory. Therefore, whether the instrumentation can be able to be installed at a "typical" state-owned dam was evaluated.

The recommendation was to install IoT Flood Sensors to monitor for overtopping, activation of the emergency spillway, and rapid drawdown/loss of pool. For testing and evaluating the accuracy of the IoT Flood Sensors, a low-pressure transducer that has been used successfully at dam sites was also recommended to serve as a control.

Three vendors that were also collaborating with DHS S&T provided IoT sensors that were used for this project: Evigia, Intellisense, and Progeny. Each vendors' sensor used a pressure transducer probe to measure water pressure and convert the pressure to a corresponding depth. Although they provided the same data, each of the sensors used slightly different technologies, different form-factors, and had different installation procedures.

3.3.2 IOT Flood Sensors Application

The likelihood of dam failure is minimal but may result in very high consequences. Many of the state- owned dams in the Commonwealth have little or no instrumentation and communities and property owners surrounding dams are typically unaware of any potential flooding risks. Due to the remote nature of many of these dams an issue may not be known until a state- or dam owner-initiated inspection is conducted.

The primary focus of the flood sensors is to promote hazard awareness and mitigation. The sooner hazards associated with dams can be identified and evaluated the more planning is possible for mitigation efforts including repairs, evacuation, and response. IoT sensors placed upstream and downstream of a dam will monitor water levels associated with the reservoir (lake) and of levels coming out of the dam. Any significant increase or decrease in water levels can potentially signify overtopping or a breach scenario and notifications in place or trigger warnings that will alert the dam owner to implement emergency actions. In the actual event of a dam breach, communities with appropriate warning systems may be given timely notice, saving lives and injuries by allowing people to evacuate promptly and responders to be ready when needed.

In addition to hazard mitigation, the sensors provided additional value. Many of the reservoirs that are monitored are used for water supply for local communities. In some cases, drought is a serious threat to community water supplies. The sensors provide an expedient and convenient method to monitor water supply via reservoir levels. Making this data public also provides a means to communicate with the community and encourage ownership in water conservation and utilization efforts.

Installation of the sensors used in this project was relatively simple and was conducted in a few hours at most. Most of the sensors are installed on a 't'-post driven into the ground near the water intended to be monitored. The node, batteries, and solar components are installed on the t-post. The pressure transducer sensors are placed in the water and the cable is either buried or protected in conduit.

The low cost and ease of implementation of IoT sensors allows communities to better prepare for dam- related incidents by allowing investment in successful response and recovery strategies. By employing these types of systems, communities may contribute to their overall resiliency against dam-related risks and insurance costs by leveraging these systems for Community Rating System (CRS) flood insurance discounts.

3.3.3 Drone Selection

In addition to the water level sensors, a drone was also used for evaluation and monitoring of selected dams. The use of a drone was recommended for monitoring for Internal Erosion/Piping (seepage) and slope stability. Modern drones can fly with little user input and collect very accurate imagery data quickly and reliably. DOW chose to investigate drone usage as an inexpensive way to routinely inspect dams for change.

The drone provides the capability to quickly collect aerial imagery and accurate elevation data at the dams. These imagery and data can then be compared to historic data to identify changes and areas of interest. For example, if an area of dam was subsiding a few inches each year, this could be an indicator of issues to investigate further. The ability of an inspector on the ground to identify this small change is difficult, however comparing data in a year over year manner makes this change evident.

Traditionally, dams are inspected by personnel walking the dam and visually looking for defects. These efforts are generally costly and time consuming. Due to recent improvements with drone technology that have drastically reduced the cost and improve the reliability and accuracy, DOW evaluated drones to regularly inspect dams and monitor change indicators. While a traditional, in-person inspection must be performed to both establish a baseline and comply with inspection requirements a drone may be used to easily monitor for changes.

Multiple drones were evaluated for cost, reliability, ease of use, and sensor quality. Modern, low-cost drones do not use traditional LIDAR to collected topography, but instead use a high-quality camera and computer processing to create a topographic representation of the dam that is very similar to LIDAR.

A combination of instrumentation and drone monitoring was viewed to be applicable at most of the dams regulated by DOW and was relatively cost effective.

3.3.4 Calibration and Threshold

Sensors that detected water level (IoT Sensors and Pressure Transducer), water levels triggers were set to detect the following events:

- Water level above dam crest (overtopping)
- Water level within 1' of dam crest (potential for overtopping)
- Water level above emergency spillway crest (emergency spillway active)
- Water level within 1' of emergency spillway crest (potential for emergency spillway to become active)
- Water level more than 1', 2', and 5' below normal pool (potential loss of pool)

To determine these trigger levels, as-built drawings of the dams were reviewed to determine the normal pool elevation, emergency spillway crest elevation, and dam crest elevation. Depths recorded when the instruments were first installed were assumed to be at the normal pool elevation. Elevations for the crest and emergency spillway were then correlated to depths for the instruments and used to set the trigger elevations. Additional triggers were set at the sites for upstream and downstream flood conditions that may impact surrounding structures were set based on a review of available topography. For the testing phase, additional trigger elevations were also set

at lower elevations to verify that the trigger notifications were functioning as expected.

3.3.5 Data Collection and Evaluation

All the IoT sensors collected and reported water levels on a regular basis. The reporting time could be modified for the sensors, but in general a reading was taken every five minutes and uploaded via cellular telemetry every 15 minutes.

In addition to water levels, the sensors also collected other atmospheric readings. Generally, all the sensors could collect the following additional data:

- Water Temperature
- Atmospheric Temperature
- Barometric Pressure
- Rainfall (with additional equipment)

Although all the readings were collected, through the course of this project, only water level was routinely monitored and analyzed.

Data for the various sensors was collected by cellular telemetry. The data was uploaded the vendors' respective servers and where it was accessible to viewed and download. DOW downloaded the data so that it could be aggregated and compared. The sensor manufacturers used different formats and storage systems for the data, so each had its own method for collection.

For a detailed plot comparison, sensor feeds were acquired from the four sensor vendors for four different sites across Kentucky over a seven-day period in February 2019. Daily total precipitation data were acquired from Kentucky Mesonet at Western Kentucky University (WKU) (https://www.kymesonet.org/) for four sites across Kentucky that were close to each of the dams (Table 5).

Table 5 Selected Mesonet sites and approximate distances and directions from research sites

Research Site	Mesonet Site	Approximate Distance	Direction
Clements Lake	Rowan County MRHD	3.1 miles	Northwest
Freeman Lake	Hardin County CCLA	6.5 miles	Southwest
Guist Creek Lake	Shelby County WADD	7.9 miles	South
Willisburg Lake	Mercer County HRDB	17.7 miles	East

The data acquired were standardized in order to compare water level readings from different sensors at a given site because water level was reported differently by each sensor vendor. In addition, the sensors were not necessarily calibrated to one another. To account for variations in calibration, the units were standardized and then the initial water level value (very first reading) for each sensor was determined for the

given time period, and the difference from this initial value was calculated for each data point (Data Point Value minus Initial Value).

Standardized values were intended to represent the change in water level over time for a given sensor, with positive values corresponding to increased water level and negative values corresponding to decreased water level. Standardized values were plotted as a function of time to facilitate visual comparison of water level readings from different sensors at a given site.

3.3.6 Follow on Sensor Testing

Following the initial testing of sensors, DHS S&T supplied an additional 133 beta sensors. "Beta" sensors had various improvements from "alpha" sensors; generally speaking, the "beta" sensors are one iteration away from production sensors. Using these sensors, DOW has made initial attempts to begin creation of the flood warning system across several dams. Due to additional issues with the beta sensors, DOW was not able to fully deploy the flood warning system as planned.

Additional dams were evaluated for sensor installation and were selected based on proximity to the Lexington and Frankfort, KY region prioritizing high hazard and poor condition dams. In addition, dams for critical water supply were considered. Sensors at selected dams were installed in the pool, usually near the dam, depending on the dam, sensors were often installed in the outfall as well.

Reliability issues with the beta sensors continued to arise so a significant number were held in reserve as replacements. In addition, there was a significant cellular service costs associated with the sensors, to limit these extraneous costs and to ensure sufficient coverage for the study, not all sensors were installed.

3.3.7 Vandalism and Tampering

Based on experience with the alpha sensors, a few modifications were made when deploying the beta sensors. All the external antennas were attached using blue thread locking compound also known as, Loctite. This makes is more difficult to remove the antennas without the use of tools. Additionally, a label was applied to the sensor showing that is was for flood warning and giving contact information for DOW. Finally, to limit the concerns about surveillance, cameras were not installed on the sensors whenever possible. These modifications mostly limited the vandalism issues.

3.4 Conclusions and Future Work

Due to various issues, DOW was not able to fully implement a statewide early dam warning system. However, this is still a priority for DOW, and the agency is actively pursuing this goal via a FEMA Hazard Mitigation Grant Program (HMGP) application. The statewide warning system is intended to include a single dashboard that allows users with various agencies to view current and historical water levels at the monitored dams in Kentucky. In addition, users may subscribe to alerts when water levels reach a certain threshold or water level change is detected that surpasses a given rate.

Furthermore, DOW desires to continue identifying collaborations to implement warning sensors for differing use cases including levees, low water crossings, and municipal stormwater applications to address pluvial flooding. Varying sized communities and partners have been identified for potential opportunities.

3.5 Sample Data Plots

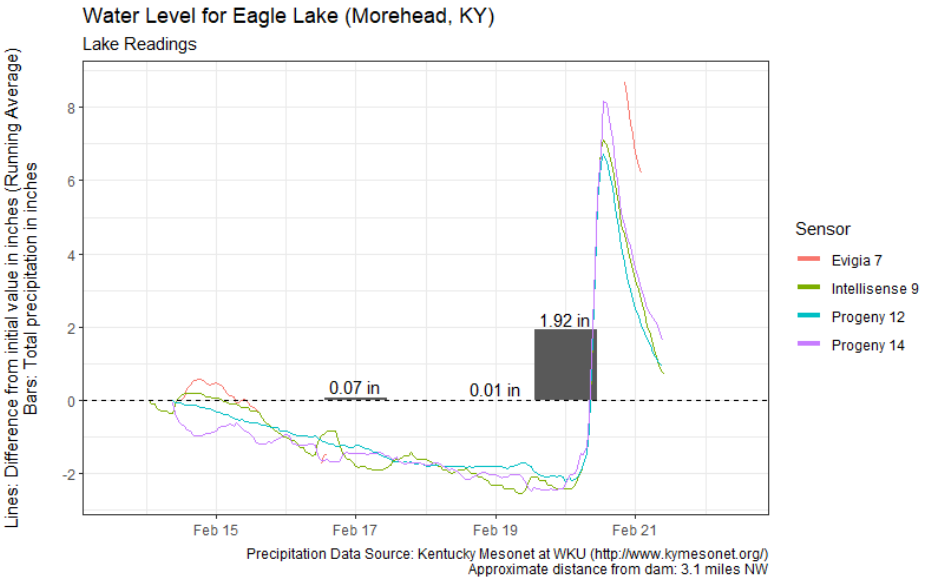


Fig. 12: *Water Level Comparison of Eagle Lake Dam Readings and Deployed IOT Flood Sensors*

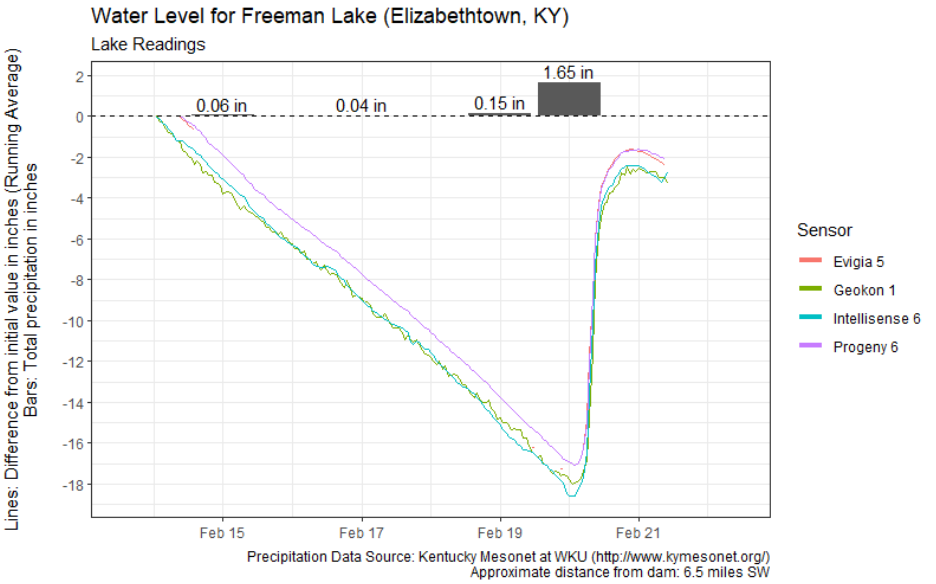


Fig. 13: *Water Level Comparison of Freeman Lake Dam Readings and Deployed IOT Flood Sensors*

3.6 Site Location Photos



Fig 14: *Sensor at Willisburg Lake*



Fig 15: *Sensor at Freeman Lake*



Fig 16: *Sensor at Willisburg Lake*



Fig 17: *Sensor at Freeman Lake*



Fig 18: *Sensor at Freeman Lake*

3.7 Drone Data Samples

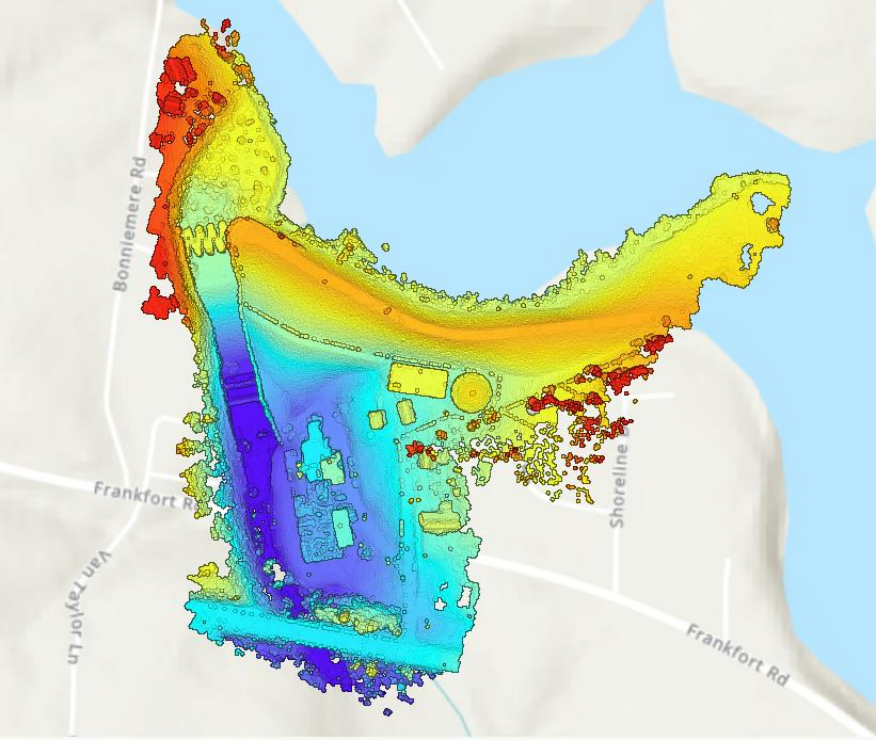


Fig. 19: *LIDAR data showing elevation from drone flight of Guist Creek Dam*

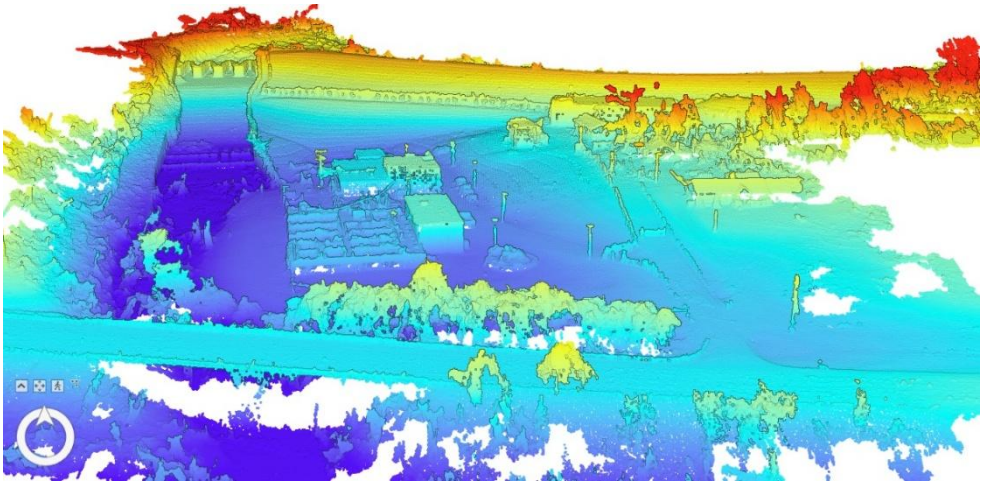


Fig. 20: 3-d representation of LIDAR data from drone flight of Guist Creek Dam

4. Key Themes, Questions, and Additional Readings

4.1 Key themes

Key themes that emerged during the CFRSS initiative were:

- Co-creation with communities is a core tenant of civic innovation.
- Low-cost flood sensors offer reliable, scalable technology for densifying flood monitoring networks and improving early warning systems in collaboration with community risk managers and infrastructure operators.
- Observable flood data that is empirically can served as a catalyst for increasing and targeting flood risk reduction investment.

4.2 Discussion questions

- What do you consider most important when developing a community flood risk reduction plan?
- What are the most common approaches for flood monitoring? What are the limitations of these solutions?
- How would you plan a flood sensor monitoring network deployment? How would you integrate low-cost IoT flood sensors?
- How would you share this information for early warning systems?
- This publication presented use cases – Charlotte, NC and the state of Kentucky. What use cases can you think of for the area where you live?

4.3 Additional Readings

- Charlotte-Mecklenburg Flood Risk Tools and Sensors – Technical Resources – https://charlottenc.gov/StormWater/Flooding/Pages/FloodSensorsTechnicalResources.aspx
- Critical Infrastructure and Flood Risk Management Innovation for Dam Safety: Kentucky Division of Water Report of Findings –

https://www.dhs.gov/sites/default/files/publications/836_Flood-Apex_Kentucky-Dam-Safety-Project-FactSheet_180403-508.pdf

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Improving Dam Safety with enhanced simulation and modeling capabilities

Nuttita Pophet, Marcus McGrath, Mohammad Al-Hamdan, Paul Smith[26], Gokhan Inci, James Demby, and Preston Wilson[27]

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Abstract

Water infrastructures, which includes dams and levee systems have traditionally been an important component of structural protection against floods and, due to their importance, are identified as one of the 18 Critical Infrastructure by DHS. Failure of dams and levees may lead to catastrophic floods that could potentially cause loss of life, urban and agricultural property damage, and environmental degradation. The majority of dams in the US are privately owned and lack adequate emergency action plans due to the cost, lack of expertise and resources, and understanding of the risk and consequences of dam breach failures. While the US coordinated dam safety at the National level, it remains primarily the responsibility of the states. Given these challenge and the complexities of dam safety assessments, dam-break modeling has become an increasingly efficient approach toward understanding the consequence of dam failure on human life and property. Led by the DHS S&T, user friendly dam breach modeling tools are being delivered to state dam safety programs that are enhancing their capabilities. This chapter describes those efforts and the value of integrating scientific advances into dam safety operations through nationally coordinated research and development.

Keywords:

Dam safety, simulation, modeling, GIS, risk assessments

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1. Introduction

"Dams bring water, power, flood control, recreation, economic possibilities, and many other advantages to people. But people must understand that safe operation and maintenance is key to sustaining these advantages and avoiding potential disaster." (ASDSO 2012)[28]

Flooding remains one of the leading weather-related causes of death in the U.S. according to the National Oceanic and Atmospheric Administration (NOAA). NOAA's Natural Hazards Statistics reflect an annual average of 82 flood-related deaths between 1985-2016, while the yearly averages for tornadoes and lightning are 72 and 49, respectively. The U.S. Department of Homeland Security (DHS) is committed to using cutting-edge technologies and scientific talent in its quest to make America safer. The DHS Science and Technology Directorate (S&T) is tasked with researching and organizing the scientific, engineering, and technological resources of the United States (U.S.) and leveraging these existing resources into technological tools to help protect the homeland. DHS S&T established the Flood Apex Program in response to a direct request from Federal Emergency Management Agency (FEMA). The Flood Apex is designed to reduce fatalities from flooding events; reduce property losses from future flood events; support community flood resiliency; and provide flood predictive analytics tools for FEMA and other stakeholders.

Water infrastructures, which includes dams and levee systems have traditionally been an important component of structural protection against floods and, due to their importance, are identified as one of the 18 Critical Infrastructure and Key Resource (CIKR) areas by the National Infrastructure Protection Plan (DHS, 2009). Failure of dams and levees may lead to catastrophic floods that could potentially cause loss of life, urban and agricultural property damage, or environmental degradation. The combination of the catastrophic floods and the loss of the various services provided by the failed dams could also lead to cascading failures in other CIKR areas. Given that 65% of the dams in the National Inventory of Dams (NID) are privately owned, the leading cause for the lack of EAPs is probably the cost of detailed dam-break studies. Many dam owners do not understand the risks involved or their personal liability in case of a failure. Although the majority of dams are privately owned, the dam safety is under the responsibility of the states. The situation is further complicated by the fact that the hazard classification of dams may change in time due to downstream development. The states have neither enough budget nor enough personnel to monitor thousands of dams under their jurisdictions continuously.

While dams provide many benefits to society, historical dam failures have caused catastrophic floods, leading to loss of life, property damage, environmental

[28] Association of State Dam Safety Officials (ASDSO) (2012). Living with Dams: Know Your Risks Factsheet. April 2012

degradation, and cascading failures (Altinakar, 2009). Thus, dam-break modeling has become an increasing tool for understanding the consequence of dam failure on human life and property. Dam-break models consist of two components: (1) estimation of breach hydrograph and (2) routing the breach hydrograph through the downstream floodplain (Ammar, 2021). The dam breach hydrograph is characterized by the magnitude of peak discharge and the time to peak discharge. The magnitude of the peak discharge directly affects the inundated area, while the time to peak discharge is important to warn the people at risk (Kalinina, 2016). The breach hydrograph can be obtained using breach parameters to predict the breach development and compute the breach outflow based on the breach progression. To route the breach hydrograph downstream, the main elements in a simulation include (1) model inputs: the breach hydrograph, topography, and land use data, (2) model types, flow equations, and numerical schemes, and (3) output: flood inundation, maximum flow depth, arrival time, and maximum flow velocity.

There are many two-dimensional modeling software options available to facilitate the estimation of breach hydrograph and the inundated area of a dam failure. Some widely used software include HEC-RAS 2D, FLO-2D, TELEMAC-2D, MIKE 21, MIKE FLOOD, and Decision Support System for Water Infrastructural Security (DSS-WISE) Lite. Examples of dam-break studies using these software products include Haltas et al. (2016), who used HEC-RAS and FLO-2D to investigate flood inundation in an urban area due to a possible failure of Urkmez Dam in Izmir, Turkey. Yakti et al. (2018) applied HEC-RAS 2D to simulate the flooding induced by the failure of the Way Ela Natural Dam. Dat et al. (2019) used MIKE FLOOD to simulate and construct inundation maps for the downstream area of Tra Khuc – Song Ve River basin. Pilotti et al. (2020) tested HEC-RAS 2D and TELEMAC 2D against the discharge hydrographs measured in a historical physical model to analyze the consequences of the hypothetical collapse of the Cancano I dam (northern Italy) and the propagation of the resulting dam-break wave along the downstream alpine valley.

The above-mentioned software products vary widely in the equation used, numerical schemes, computation methods, ease of use, customizability of inputs, and format of results. For the DSS-WISE Lite system, a web-based system developed by the National Center for Computational Hydroscience and Engineering (NCCHE), the University of Mississippi, simulations can be set up very quickly with minimum input data from users. Input files are automatically prepared using input data and national data sets. Extremely high computational speeds are achieved, as pointed out by Salt (2019) that the DSS-WISE Lite runtime is incredibly fast, and its accuracy appears comparable to that of a similar HEC-RAS model. However, the results are drastically different when including terrain modifications in the HEC-RAS simulation for areas where significant terrain features are not captured. It is noted that the major update of DSS-WISE Lite on November 7, 2021, includes the capability to modify terrain when setting up a simulation. Correa (2019) studied a dam-break flow for Bidwell Lake Dam and found that simulation results of the HEC-RAS model and DSS-WISE Lite model are similar, especially almost identical inundation extents. Larrauri (2020) used DSS-WISE Lite to predict the breach hydrograph and inundation area for dams in the Cumberland

River Basin and proposed a framework to complement Flood Insurance Rate Maps (FIRMS) to help identify "hot spots" beyond the current dam hazard classifications. DSS-WISE Lite was also used during the Oroville Dam spillway incident in 2017, dam safety emergencies in Texas during Hurricane Harvey in 2017, emergency dam-break flood simulations in Puerto Rico during Hurricane Maria in 2017, and emergency simulations during Hurricane Florence in 2018.

2. Background

Historically, obtaining an accurate flood inundation map by using a numerical model could be a slow, difficult, and expensive process which limited use of such beneficial models. So, in 2011, DHS S&T responded to the need for improved modeling capabilities by funding NCCHE to develop and operate DSS-WISE Lite to address the needs of having an efficient and easy to use tool to facilitate flood inundation modeling and mapping and to support decision making. The improved capabilities offered by this system will be detailed in a later section. The U.S. Army Corps of Engineers (USACE) also contributed to this effort. In 2012, the DSS-WISE Lite became accessible through a user interface called DSAT (Dams Sector Analysis Tool), which expired in November 2014. In September 2015, FEMA National Dam Safety Program signed a five-year contract with NCCHE to develop a standalone version of DSS-WISE Lite that was hosted on a cluster of servers at the NCCHE, whose service became available on November 8, 2016, and also supported its operations and maintenance since then. In September 2018, the US DHS S&T signed another contract with NCCHE to provide further enhancements and improvements to the DSS-WISE Lite web-based service. These enhancements were released to the dam safety community as part of a "Version 3.0" update on November 7, 2021, almost five years to the day from the system's original unveiling. In addition to Federal support, developments to the DSS-WISE Lite system have been funded by States, most notably the California Department of Water Resources through Sacramento State University.

Since its release, the DSS-WISE Lite system has been providing dam-break and breach flooding inundation modeling for over 1,500 users in the dam safety community. These users have submitted over 48,000 simulations as of June 2022, with a success rate of 99.9% which produced either results or a helpful error to guide the user on how to correct the issues found. Of the simulations that produced results, over 87% did so within 30 minutes from the time of submission, and 92% completed in less than one hour. Users of DSS-WISE Lite have submitted simulations in all fifty states and Puerto Rico, as shown in Figure 1. This high demand from all over the country clearly demonstrates the level of buy-in and usefulness of the system to the dam safety community.

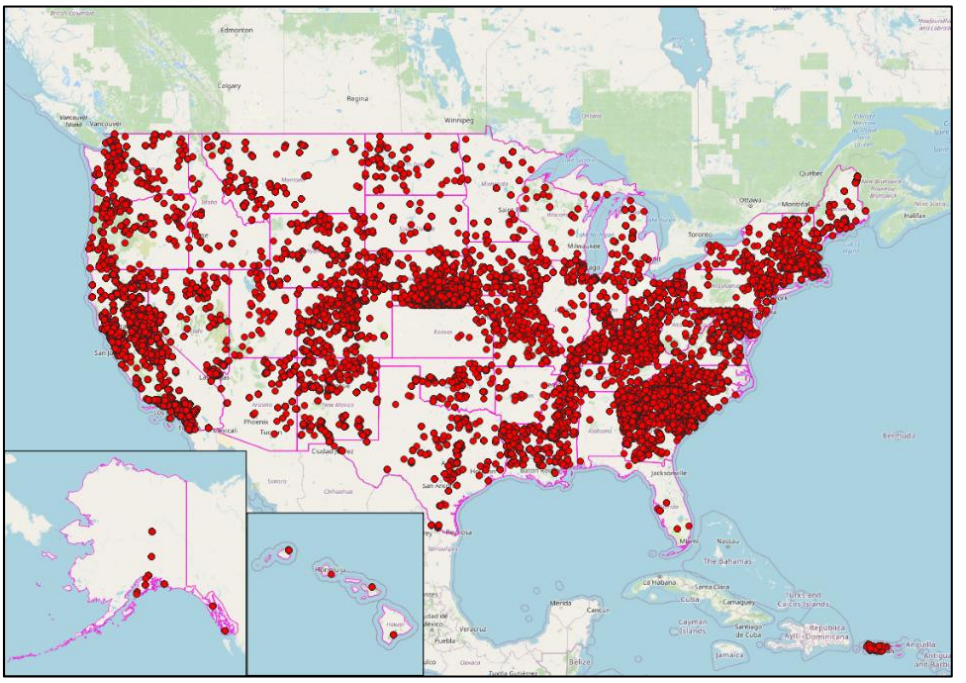


Fig. 1: *Locations of DSS-WISE Lite Simulations as of June 2022*

In addition to dam breach analysis capability, the system also provides an analytical module for assessing the human consequences of dam-break floods-. The DSS-WISE Lite Human Consequences Module (HCOM) uses flood simulation results from DSS-WISE Lite to generate PAR analysis results using census block population data from the Census Bureau and gridded nighttime and daytime population data from LandScan USA. The module also produces maps of flood hazard risks for people caught outdoors and indoors and potentially lethal flood zones (PLFZ) for children and adults.

3. Overview of DSS-WISE Lite and its Advantages

DSS-WISE Web is the Internet-based arm of DSS-WISE which provides access to a secure, web-based environment consisting of a graphical user interface and map server used to set up fully automated two-dimensional dam-break/levee-breach modeling and mapping at various resolutions currently available 24/7 and free of charge. After being accepted in a group through the Group Management module, users have access to the Viewer and its Prep Tool module along with the simulation results module. The DSS-WISE Lite Prep Tool is a graphical user interface (GUI) with minimized user input and real-time error checking that provides quick and intuitive simulation setup in just a few simple steps. Figure 2 shows the Viewer and Prep Tool. A simulation can be set up and submitted in as little as a few minutes, after which the automated system takes over and prepares all the necessary data to adapt to the conditions of that particular scenario. The user can choose to model the breach either by simulating the reservoir hydrodynamics or by providing a hydrograph prescribing water to be released downstream of the breached dam. In the former case, the initial pool elevation and

volume of the reservoir are set by the user and represent a sunny day failure event with no downstream releases before the breach initiation. The simulation domain is tailored the user's preferences within their area of interest, taken from the best available, high-resolution digital elevation models (DEMs) from the USGS 3D Elevation Program. The DEM is conditioned to remove the reservoirs' water surfaces, which are then replaced by an estimated bathymetry generated from the user-supplied stage-volume information. This process allows the reservoir hydrodynamics to be calculated with the fully verified and validated, two-dimensional numerical solver at the core of DSS-WISE as opposed to being modeled as storage areas or boundary conditions as in other models. Simulations are scheduled to run on available compute servers in a first-in, first-out basis. After completion, the simulation results are processed to provide a rich set of GIS-compatible files along with reports and other datasets. All of the results are visible on a dedicated page on the DSS-WISE Web site for visualization, analysis, and download from any computer, including mobile devices.

All of the steps from simulation set-up, progression through the processing stages, and final results presentation happen via the online portal without the need for human intervention. The time-consuming and difficult parts of model input file preparation, DEM conditioning, mesh generation, scheduling processing power, etc. have been automated away from the end user's perspective. This has numerous benefits:

- The user does not need to be a modeling expert in order to get a reasonable dam break flood inundation map. This lowers the barriers to entry and allows more of the dam safety community to participate in these efforts.
- The user only needs to provide a minimal amount of information about the dam and reservoir in their scenario, and they do not need to manually set up input files and provision compute resources like they would in order to run a legacy dam-break model. This allows users to submit many simulations in a short amount of time, which could be various scenarios involving the same dam, or many different dams in their portfolio.
- The system is very quick to return results to the user in the vast majority of cases. This allows users to run several simulations to iterate on and improve their simulation results if desired.
- The ease and speed of set-up, along with the fast turn-around time for results, makes DSS-WISE Lite an ideal decision support tool for use in emergency situations.
- Since the use of DSS-WISE Lite is free to the user, combined with the ease and speed of scenario set-up, this results in drastically reduced cost in terms of personnel, equipment, and software license fees. Without such a tool, one would either have to provision expensive computer hardware and set up a model by hand or acquire the (likely costly) services of an engineering firm.

The simplified user input and automated data preparation give users large advantages over legacy modeling software in terms of cost and time, resources which are scarce for many dam safety offices.

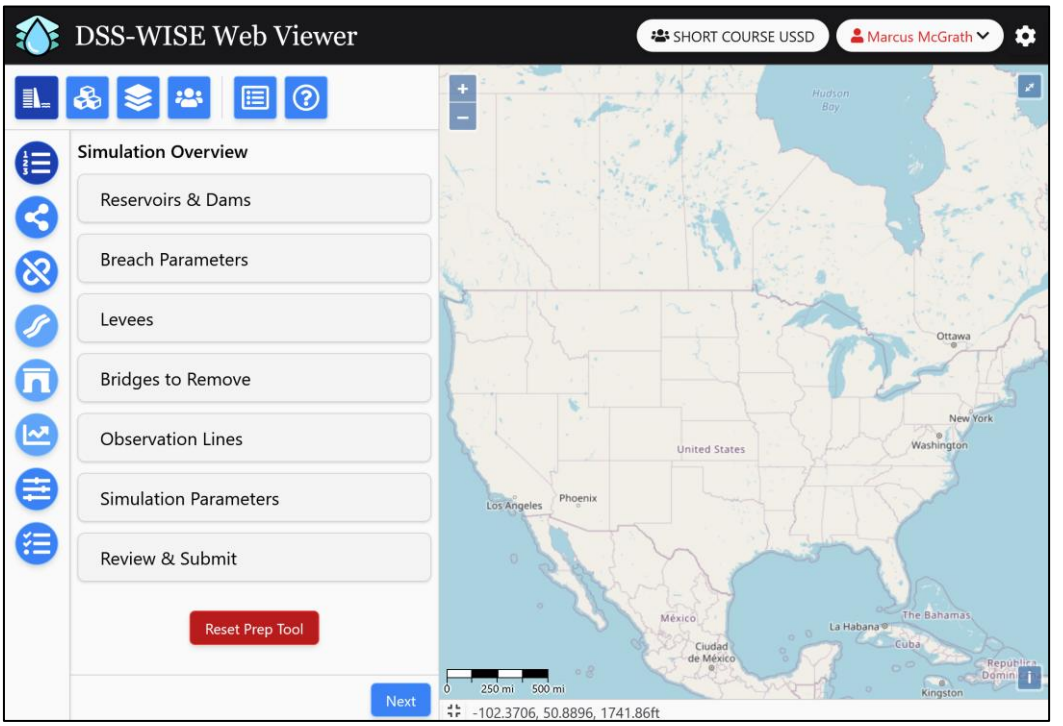


Fig. 2: DSS-WISE Web Viewer and Prep Tool

4. Alignment with the Flood Apex Program and National Dam Safety Program

The Federal government has been using the National Dam Safety Program (NDSP) to protect Americans from potential dam failures for the last 30 years. The objectives of NDSP are to:

- ensure that new and existing dams are safe through the development of technologically and economically feasible programs and procedures for national dam safety hazard reduction;
- encourage acceptable engineering policies and procedures to be used for dam site investigation, design, construction, operation and maintenance, and emergency preparedness;
- encourage the establishment and implementation of effective dam safety programs in each state based on state standards;
- develop and encourage public education and awareness projects to increase public acceptance and support of state dam safety programs;
- develop technical materials for Federal and state dam safety programs;
- develop mechanisms with which to provide Federal technical assistance for dam safety to the non-Federal sector; and
- develop technical assistance materials, seminars, and guidelines to improve security for dams in the United States.

Three of the five 2014-2018 FEMA Strategic Plan priorities established by the FEMA Leadership are supported by the NDSP:

- Be Survivor-Centric in Mission and Program Delivery,
- Posture and Build Capability for Catastrophic Disasters, and
- Enable Disaster Risk Reduction Nationally.

The National Dam Safety Review Board (Review Board), monitors the safety of dams in the United States, the States implementation of NDSP requirements and advises the FEMA Administrator on national dam safety policy, and the Interagency Committee on Dam Safety (ICODS), which coordinates among Federal agencies on dam safety issues and collaborates with the Review Board to ensure consistency and support between the Federal and non-Federal elements within the dam community, are both chaired by FEMA.

Moreover, under the National Dam Safety Program Act, FEMA has a statutory requirement at 33 U.S.C. § 467: US Code - Section 467G-1 (Training) to, at the request of any State that has or intends to develop a State dam safety program, provide training for State staff dam safety and inspectors. FEMA also has a statutory requirement at 33 U.S.C. 467G (Research) to carry out a program of technical and archival research to develop and support:

- Improved techniques, historical experience, and equipment for rapid and effective dam construction, rehabilitation, and inspection;
- Devices for the continued monitoring of the safety of dams;
- Development and maintenance of information resources systems needed to support managing the safety of dams; and
- Initiatives to guide the formulation of effective public policy and advance improvements in dam safety engineering, security, and management.

5. Recent Developments to the DSS-WISE Lite System

DSS-WISE Lite was designed from the beginning to be extremely easy to set up by a novice modeler with the minimal amount of input data required. This core design philosophy has remained while continuing to be developed with new features and capabilities. The developments enable further ease of use, expand the types of scenarios able to be simulated, and increase the toolkit available to more advanced modelers. The most recent major release occurred in November of 2021, which included a complete redesign of the Viewer and Prep Tool module as seen in Figure 2. A partial list of the most notable recent developments includes the following:

- Allowing the user to model multiple dams in series. Each impounded reservoir is removed from the DEM and replaced with its equivalent estimated bathymetry as previously was only possible for a single reservoir. This allows the downstream initial water surface elevations to be controlled instead of relying on the level present in the DEM.

- Providing the ability to model linear terrain features such as levees and culverts with given elevations and width. This new ability to modify the DEM is a powerful tool in the hands of a skilled modeler.
- Enabling the user to load a new simulation from a previous one. This allows running multiple scenarios from the exact same inputs, and users no longer have to start from scratch to correct errors, which saves time.
- Numerous additions and improvements to the Prep Tool to set up simulations, including a search tool to import data from the National Inventory of Dams and a breach parameter calculator which automatically generates values from a multitude of semi-empirical equations.
- Improvements to the results page after a simulation has finished running, including visualization of all the results layer right in the user's web browser, a point query tool for interrogating the results layers, and improved mapping layers and options. The simulation results package also now provides information about the stage-volume curve imposed for each reservoir as well as the time history of elevation and volume remaining in the breached reservoir.
- Updated USGS 3DEP 1-meter elevation data. As the availability of this dataset increases, the data can be ingested into DSS-WISE Lite simulations, increasing the accuracy of simulations in those areas.

In addition to these recent developments, the system's operations and maintenance continues to be funded by FEMA, and many new improvements are anticipated to be funded in the near future.

7. DSS-WISE Case Study

7.1 Study Area

On May 19, 2020, at approximately 5:35 p.m. EDT, a section of the eastern side of Edenville Dam located on the Tittabawassee River in central Michigan collapsed suddenly during a rainfall event that resulted in a record-high water level within the impounded Wixom Lake (France et al. 2022). Much of Wixom Lake drained into the Tittabawassee River and flowed into Sanford Lake. At about 7:19 p.m., the Sanford Lake level rose above the crest of the fuse plug spillway at the Sanford Dam, and the fuse plug began to erode. At around 7:45 p.m., the fuse plug began to wash out, and there was an increase in release capacity at Sanford Dam. However, the combined release capacity of the fuse plug spillway and the gated spillway was insufficient to prevent the continued rise of the Sanford Lake level, leading to an overtopping breach failure of the Sanford Dam at about 8:20 p.m. The combined outflows from the failure of Edenville Dam and Sanford Dam and runoff from the natural watershed inundated downstream areas of Midland County and Saginaw County. The flooding resulted in widespread damage and destruction to buildings, homes, roads, utility infrastructure, and natural resources. Approximately 11,000 residents were successfully evacuated with no serious injuries or loss of life reported. More than 4,000 structures were reportedly impacted by the floodwaters, with estimated losses of roughly $245 million (Galvin 2020).



Fig. 3: *Edenville and Sanford Dam locations and images of (a) Edenville Dam breach, (b) Edenville Dam after the failure (c) the fuse plug spillway of Sanford Dam being overtopped, and (d) the entire embankment of Sanford Dam being overtopped.*

7.2 Simulation Setup and Model Inputs

The failure event of the Edenville and Sanford Dams was modeled using the DSS-WISE Lite web-based system. Data sets used by the system include terrain data from USGS 3D Elevation Program (3DEP), levee data from the USACE National Levee Database (NLD), and land cover data is from the National Land Cover Database (NLCD), with Manning's for different land covers defined. A hydrograph-type simulation was used in the model setup. The breach hydrograph located at the Sanford Dam was obtained by combining the hydrographs from two simulations. One was set up as a reservoir-type simulation where the breach was located at the Edenville Dam. The observation line was placed at the Sanford Dam to collect the flood hydrograph

contributed from the Edenville Dam failure. The same process was done with the breach located at the Sanford Dam failure, and the hydrograph of this failure was collected at the Sanford Dam. The hydrographs were combined to obtain a breach hydrograph for both dam failures. The combined hydrograph was used to run the simulation which the results are present in this article. Input parameters for all three simulations are presented in **Table 1.** All the hydrographs are shown in Figure 4.

Table 1: Input parameters for reservoir-type simulations of Edenville and Sanford Dam failure.

Reservoir Details	**Wixom Lake**	**Sanford Lake**
Normal Pool Elevation (ft NAVD88)	675.2	630.8
Normal Pool Volume (ac-ft)	36000	15000
Maximum Pool Elevation (ft NAVD88)	681.5	636.8
Maximum Pool Volume (ac-ft)	66200	60000
Failure Pool Elevation (ft NAVD88)	681.5	636.8
Failure Pool Volume (ac-ft)	66200	60000
Dam Details	**Edenville Dam**	**Sanford Dam**
Crest Elevation (ft NAVD88)	681.5	636.8
Hydraulic Height (ft)	54	36
Structure Type	Embankment	Embankment
Breach Parameters	**Edenville Dam**	**Sanford Dam**
Failure Type	Partial Breach Failure	Partial Breach Failure
Breach Invert Elevation (ft NAVD88)	627.5	600.8
Breach Width (ft)	481	890
Breach Formation Time (hr)	0.17	0

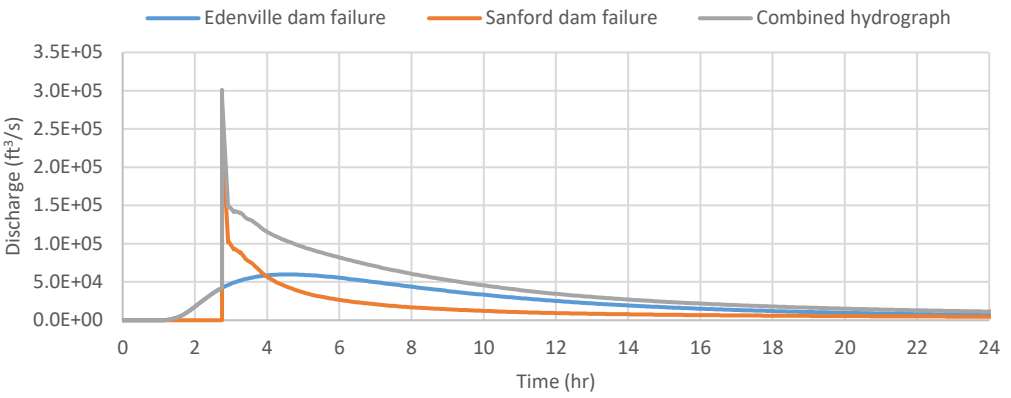


Fig. 4: *Hydrographs of Edenville dam failure, Sanford dam failure, combined hydrograph of both events.*

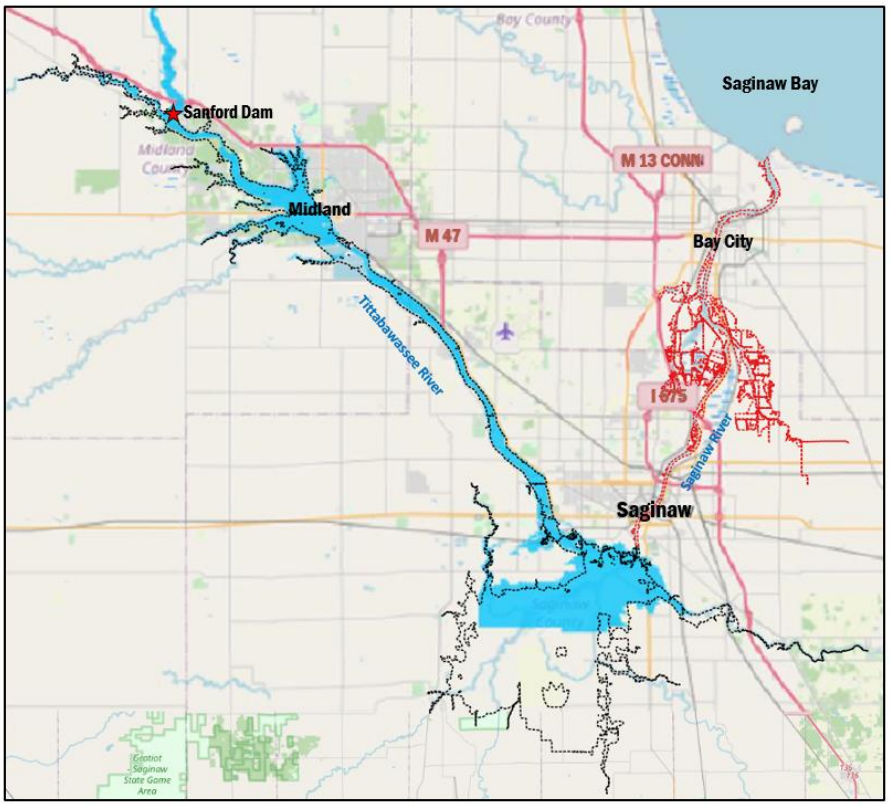


Fig. 5: *Observed (FEMA 2022, blue area) and simulated (black and red dotted lines) inundation extents for Midland and Saginaw counties.*

7.3 Main Simulation Outputs

Figure 5 shows that the simulated inundation extent agrees well with the observation boundary for the flooding in Midland and Saginaw County, except in some areas with unavailable observation data. The observation data was available for Midland County and part of the Saginaw County, covering the area south of the Edenville Dam to the confluence of the Tittabawassee and Saginaw Rivers. The simulated inundation extent covers the area south of the Sanford Dam to the confluence and from the confluence to the Saginaw Bay. The areas not included in the observation but reported as flooded in the simulation are the south of the confluence of the Tittabawassee and Saginaw Rivers and along the Saginaw River from the confluence to the Saginaw Bay, where the simulated extent is present in the red dotted line. However, those areas were reported to be flooded during the event. In the simulation, terrain data needed modification to capture realistic conditions more accurately. Figure 6 shows an example of these areas at the Pere Marquette Trail Sturgeon Creek Bridge. Figure 7 features an image of the flooded area in downtown Midland and the simulated results in a KMZ format on a Google Earth map.

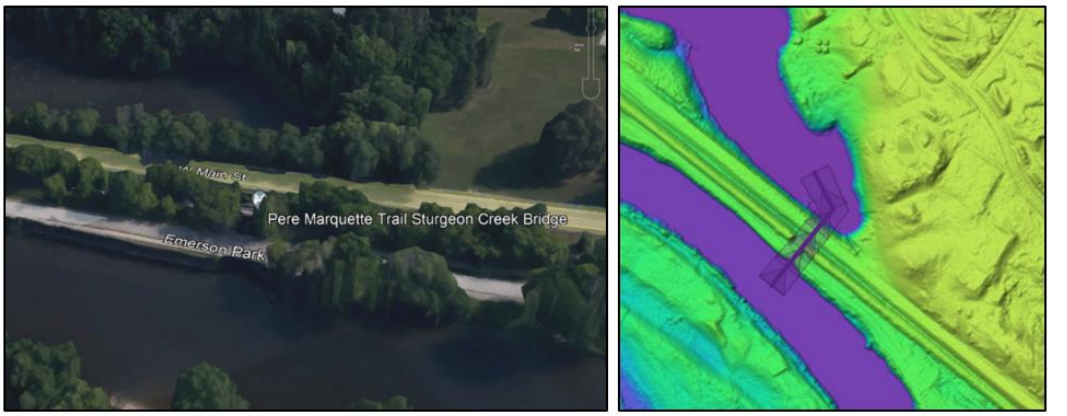


Fig. 6: *Terrain modification at Pere Marquette Trail Sturgeon Creek Bridge to create passages for water to flow: Google Earth, 2022 (left) and DEM with the polygon inside which the terrain data was modified (right).*



Fig. 7: *Downtown Midland: Observed (left) and Simulated (right).*

7.4 HCOM Simulation Outputs

Decision Support System for Water Infrastructure Security Human Consequence Module (DSS-WISE HCOM) provides an analytical module for assessing the human consequences of dam-break floods. This module produces a series of geospatial files, an MS Excel worksheet with tabular data, and a PDF final report for Emergency Action Plan (EAP) preparation, better preparedness, emergency response planning, and evacuation planning.

Analysis of People at Risk (PAR) is performed by interfacing the results of flood simulation from DSS-WISE Lite with the population data sets: 2010 Census Block data provided by the United States Census Bureau (USCB), and LandScan USA gridded population data developed and maintained by the Oak Ridge National Laboratory (ORNL).

PAR analysis results using census blocks are present both as a polygon shapefile and a spreadsheet table. Attributes of the shapefile and table include: 2010 total housing count, 2010 total population count, total area of the census block, inundated area of the census block, percent area inundated, flood arrival time, maximum flood depth, maximum DV, arrival time of maximum DV. Figure 8 shows census blocks for population count for Edenville and Sanford dam-break flood.

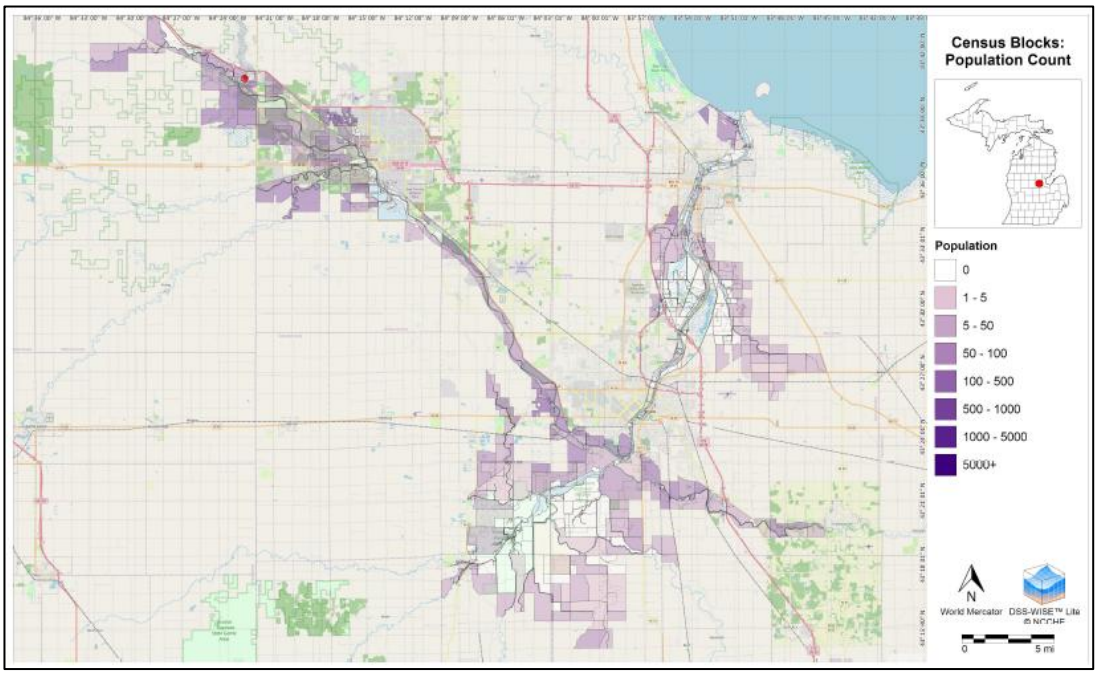


Fig. 8: *Census blocks: Population count for Edenville and Sanford dam-break flood.*

Nighttime and daytime PAR analysis results using gridded LandScan USA data present as a shapefile, tables, and corresponding plots of the evolution of inundation area and the nighttime and daytime PAR classified in ten intervals of maximum DV. Figure 9 presents the plot of nighttime PAR analysis for the Edenville and Sanford dam-break flood.

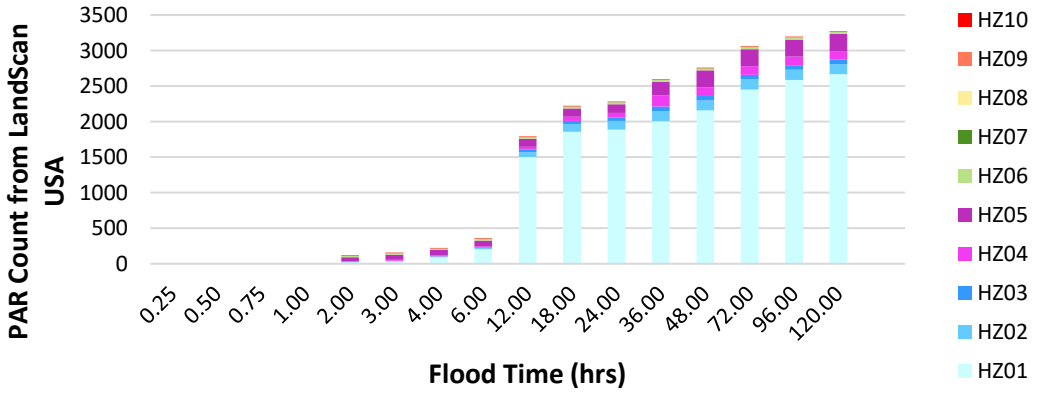


Fig. 9: *Evolution of nighttime PAR by highest flood hazard category achieved for Edenville and Sanford dam-break floods.*

Flood-hazard mapping divides the inundation extent into zones of predefined potential danger classes for humans. These classes are identified based on the ranges of the value of the maximum specific discharge DV. The ranges of DV values are different for persons caught outdoors and indoors. For people caught outdoors, a selected range of DV values define five potential danger classes representing danger levels for different population categories. For people caught indoors, the potential danger is associated with the collapse of the building. HCOM identifies five potential danger zones corresponding to collapse limits of different building types. The potential flood hazard level for people outdoors during Edenville and Sanford dam-break flood is present in Figure 10.

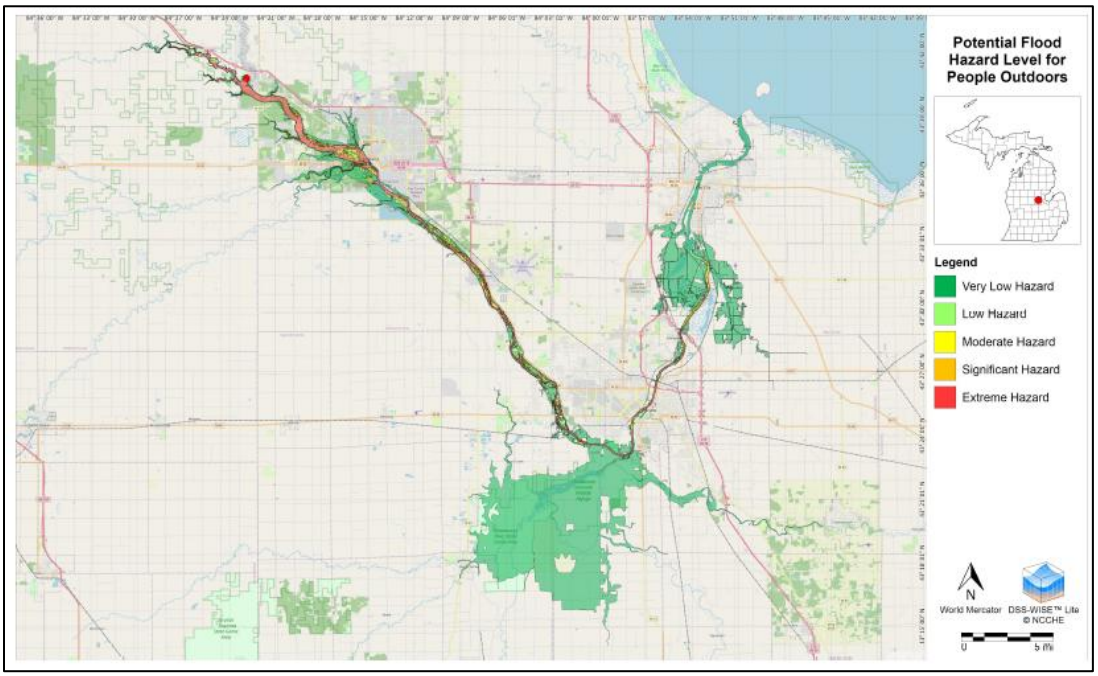


Fig. 10: *Potential flood hazard level for people outdoors for Edenville and Sanford dam-break flood.*

Potentially Lethal Flood Zones (PLFZ) are defined based on the maximum flood depth and maximum DV-value. HCOM extracts and maps the polygons corresponding to PLFZ zones for children and adults. Figure 11 presents PLFZs for Edenville and Sanford dam-break flood.

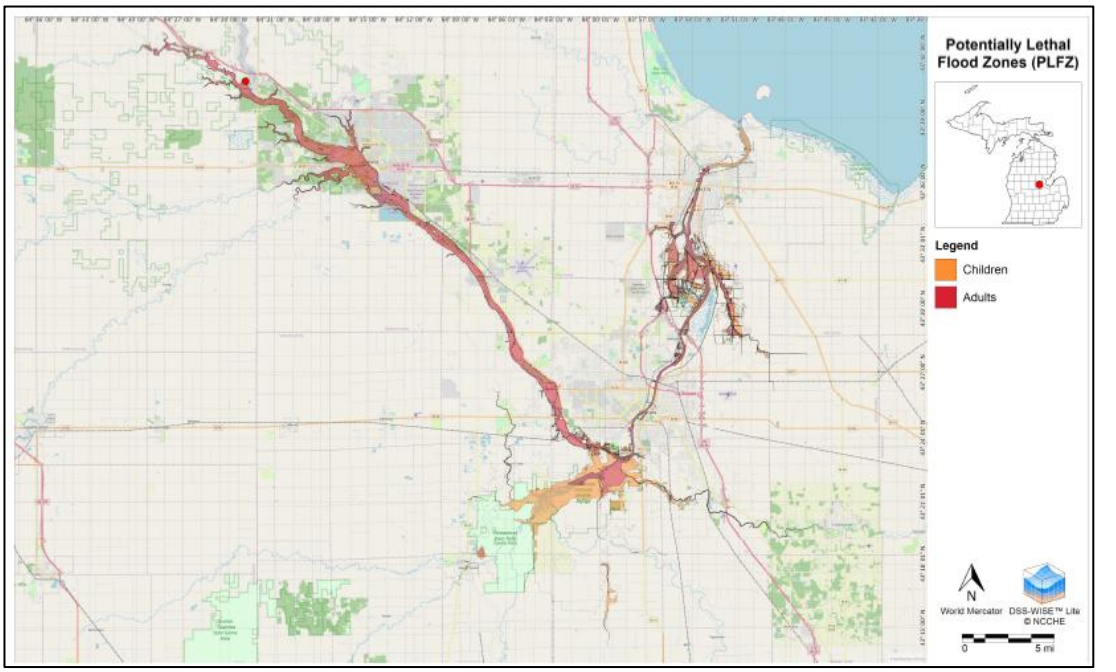


Fig. 11: *Potential lethal flood zones (PLFZ).*

8. Conclusions

The goals of the Flood Apex Program demonstrate the need for fast, accurate, and easy to use flood modeling tools in order to delineate areas of potential flooding and determine consequences from dam break events. These events may become more frequent and more severe due to climate change, aging infrastructure, and increasing population downstream of the dams. In order to address these issues, the dam safety community relies on numerical models to calculate various scenarios either before or during an emergency event. Being an online, fast, free to use dam break decision support system, DSS-WISE Lite is uniquely positioned to address the most pressing needs of the modelers while simplifying their workload through advanced capabilities. As has been shown in the case study, the DSS-WISE Lite system can produce inundation maps that compare favorably with observed historical events while requiring a minimal amount of input and effort on the modeler's part. These results, taken in the context of being a first level analysis for prioritization and screening, are adequate for many dam safety agencies, and may also be used to indicate those dams which require further, more detailed study. Recent developments to the DSS-WISE Lite system have expanded the capabilities and productivity of modelers from across the United States, and its continued operation serves to increase the level of preparedness and resilience in the dam safety community.

9. Key Themes, Questions, and Additional Readings

9.1 Key themes

Key themes that emerged during the DSS-WISE initiative were:

- Co-creation with end-users remains the most effective approach toward packaging and delivering scientific advancements to the dam safety community.
- Failure of dams and levees may lead to catastrophic floods that could potentially cause loss of life, urban and agricultural property damage, environmental degradation.
- Many dam owners do not understand the risks involved or their personal liability in case of a failure nor have the expertise and resources to adequately develop emergency action plans and risk assessments for the dams under their responsibility.
- Advanced dam breach modeling and simulations tools such as DSS-WISE that are coordinated nationally and include economic consequence projections have enhanced dam safety program capabilities across the US.

9.2 Discussion questions

- What are the key challenges for dam safety programs that dam breach simulations tools are able to address?
- What are the key benefits and advantages provided by a system like DSS-WISE?
- What kind of questions would a dam safety program want a system like DSS-WISE to help you answer?
- What are the two main components of dam breach models? How are these components characterized? What are the key elements required for a simulation?
- What kind of output needs to be delivered and in what form?
- This publication presented a use case for a section of the eastern side of Edenville Dam located on the Tittabawassee River in central Michigan. What use cases can you think of for the area where you live?

9.3 Additional Readings

- DSS-WISE website - DSS-WISE™ Web (olemiss.edu) operated by the National Center for Computational Hydroscience and Engineering at the University of Mississippi.
- DSS-WISE Lite factsheet from FEMA - DSS-WISE Lite: Web-based Automated Dam-Break Modeling/Mapping (fema.gov)
- S&T's Dam Simulation Program Saves Lives and Saves Taxpayers Nearly $50M (newswise.com) articled published on Newswire. November 2017.
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Optimizing Flood Impact analysis for disaster response: The WELL

David Judi, Mark Jensen, Xue Li, Patrick Royer, Timothy McPherson, Tycko Franklin, and John Garza[29]

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Abstract

Floods are one of the most prevalent natural disasters nationwide. Management of these events involves all levels of government and industry, but the operating environment for stakeholders is highly diverse including from on the ground first responders to state flood plain managers to federal emergency response officials. Each of these stakeholders requires flood and flood impact information that fits within their operational context while also still maintaining consistency across the diverse set of users and missions. This is particularly important during the response and recovery to extreme flood events when decisions affect the protection of life, property, and critical infrastructure systems. As such, methods and tools that are accurate and timely are essential in defining resilience to flood events. Predictive analytic tools can provide advanced warning of extreme flood events and can be used to quantify the potential impacts to population and infrastructure, yet we lack consistent approaches to connect modelers and decision makers to effectively communicate these predictive analytics. To alleviate some of the challenges in providing available predictive flood analytic data to the emergency response community, we are exploring the utilization of cloud-based technology to gather, store, visualize, and disseminate data to enhance situational awareness. This paper explores the use of cloud-based resources to advance the state of hydroinformatics and presents a prototype application of the Open Water Extreme Lookup Library (Open-WELL).

Keywords:

Predictive analytics, situational awareness, image processing

1. Introduction

"Analysts fear being wrong. Responders fear being late." (Wright 2017)[30]

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[30] Roy Wright (2017). Quote from Knight, Sandra, Tom Richardson, Chris Lenhardt, Richard A Luettich, and Ellie Graeden. 2018. *Rethinking Flood Analytics: Proceedings From the 2017 Flood Analytics Colloquium.* https://doi.org/10.17615/C6S08Z

Floods are one of the most prevalent natural disasters nationwide. In fact, more than 40% of all federal disaster declarations since the 1950s have been related to floods. The frequency and intensity of these events is increasing and can have significant physical, social, and economic impacts. These events have significant impact on both natural and built systems and have direct impact on the infrastructure systems (e.g., power, water, wastewater, communications, and transportation) that support and sustain community health. Management of these events involves all levels of government and industry. In addition, the operating environment for stakeholders is highly diverse including from on the ground first responders to state flood plain managers to federal emergency response officials. Each of these stakeholders requires flood and flood impact information that fits within their operational context while also still maintaining consistency across the diverse set of users and missions. This is particularly important during the response and recovery to extreme flood events when decisions affect the protection of life, property, and critical infrastructure systems. As such, methods and tools that are accurate and timely are essential in defining resilience to flood events. Predictive analytic tools can provide advanced warning of extreme flood events and can be used to quantify the potential impacts to population and infrastructure.

High-resolution flood modeling and simulation has shown great promise in supporting emergency responders. These predictive flood analytic tools can provide flood situational awareness relative to areas at risk, potential damage, and also the identification of safe zones (the inverse of areas at risk) for resource pre-positioning or population evacuation. These predictive tools can provide situational awareness hours and even days prior to flooding, in addition to providing situational awareness during recovery periods. However, these data are not being effectively used during response to extreme events. For example, it has become clear during previous major tropical cyclone events, such as Hurricane Harvey in 2017 and Hurricane Florence in 2018, that simulation data is not consistently made available to all parts of the emergency response community. Moreover, the presence of more than one predictive analytic product has created confusion amongst stakeholders and hinders response activities. There is significant interest in eliminating stovepipes and existing confusion and facilitating the access to predictive flood analytics to enhance situational awareness and ultimately save lives.

To alleviate some of the challenges in providing available predictive flood analytic data to the emergency response community, we are exploring the utilization of cloud-based technology to gather, store, visualize, and disseminate data to enhance situational awareness. The objective of this effort is to research approaches and develop a prototype that can leverage cloud resources and meet these emergency-response requirements. Previously, PNNL has developed a cloud-based repository of flood data, the Water Extreme Lookup Library (WELL) to support the Department of Homeland Security (DHS) Cybersecurity and Infrastructure Security Agency (CISA) infrastructure protection missions. The WELL contains thousands of pre-run simulations that can be readily queried, visualized, and downloaded. In addition, the WELL contains data APIs to facilitate ingestion of data into other environments and

workflows, such as infrastructure models that characterize the exposure, damage, and cascading impact to infrastructure operation. The utility of the WELL is to support rapid situational awareness, planned studies, and perform unique data analytics (e.g., risk). At first, the WELL contained only dam break flood simulations. Today it continues to expand coverage and will ideally include all types of floods including river, levee, and dam scenarios. The WELL currently contains over 60,000 unique flood simulations with results available on-demand for DHS CISA.

As part of the DHS S&T funded Flood Apex program, PNNL has been exploring approaches to translate this technology into an open architecture that will enable flood event response and recovery professionals to use the latest flood forecasts from multiple organizations. This technology platform, the Open-WELL, will utilize cloud computing to further the storage, visualization, and serving of flood and flood impacts data to the emergency response community.

2. Open-WELL Technology Requirements

2.1 Requirements Discovery

We reviewed the state of cloud-based flood analytics in the published technical literature, interviewed emergency response stakeholders to understand needs and requirements that facilitate response, and developed a prototype Open-WELL platform for use in flood emergency response. Research, development, and documentation of the impact that cloud-based technology has on disaster response (e.g., floods, fire, earthquake) is largely qualitative or based on other types of crises. Significant potential for reducing response times, costs, and on-site technological needs is highlighted across both the academic and business literature, but few studies exist to quantify the actual changes observed in disaster response due to cloud-based technology.

Qualitative research articles highlight a cross-cutting field posing great potential for technological progress in disaster response capacity, for providing a technological solution to long-standing disaster response challenges (e.g., on-site computing and modeling capacity), and the need to provide information to multiple end users simultaneously as well as collect data from many sources (Ujjwal et al., 2019). Most case studies focus on the services provided through cloud technologies and the potential for geographic information systems (GIS) and other integrated systems that can benefit from a cloud-based approach, but they rarely discuss the impacts of the use of those services. There remains a need to understand the impact of cloud-based technology on disaster response as opposed to presentation of theoretical frameworks for future of response (Ujjwal et al., 2020).

There are many components of cloud-based technologies that are needed to support disaster response. These include computing resources for large dataset storage and comparison, data ingestion capacity, releasing information to a large number of people in a short amount of time, and the inherent reduction in access to technology and power that occurs during and after a flood (Ujjwal et al., 2020; Quiroga et al., 2013). There are number of salient requirements for flood response planning and assessment.

Those requirements can be categorized as either computational requirements, data integration, interoperability and dissemination requirements, multiple simultaneous end user requirements, time critical requirements or continuity of response requirements.

Computational requirements refer to the vast amount of geospatial data, modeling, and analysis necessary to define areas at risk, areas to avoid, and areas requiring response and assistance during a flood event. These needs require a large amount of computing power. Ideally, these computing resources would be scalable based on the type of event and geographic region to be analyzed. Data integration, interoperability, and dissemination requirements include challenges relative to the mission aspects of disaster response, including floods. Disasters drive a dynamic timeseries of response activities. Enhanced situational awareness from a predictive analytics point of view requires gathering temporal data from a variety of sources. These sources might include multiple authoritative sources of prediction data, observations from satellite imagery or on the ground measurements, topographical information, or other non-traditional data that can support response (e.g., social media data). Importing or collecting, processing, and storing this data requires flexible storage and pipelines to automate the collection and validation of data. Moreover, processing techniques are required to help end users understand differences and similarities between multiple datasets such that these data can be effectively used to augment response activities. Multiple simultaneous response end user requirements pertain to the diversity of organizations and their members involved in the response to an emergency, including state and local response officials and first responders. These organizations rely on access to information about which areas will or have experienced flooding. This information is used to enhance decisions made in the planning, response, and recovery from extreme events. Due to the distributed nature of emergency response, these end users require simultaneous and uninterrupted access to temporally evolving information. In addition, these end users themselves may be simultaneously submitting data to support other members of the response community. Time-critical requirements describe those needs that are time dependent for success. Time is of the essence in emergency response. Modeling and analysis results must be provided efficaciously to those making decisions in a manner that minimizes the latency in the availability of data. Lastly, continuity of response technology requirements describes needs that are based on the very infrastructure that facilitates access to information about floods. In cases where important infrastructure may be damaged, inaccessible, or temporarily unusable during a flood, alternative deployment processes are necessary to limit impacts to the continuity of the response. New tools are needed to provide decentralized versions of previously described technologies.

Information, data, and analysis are used in a number of specific ways during by the emergency response community. (Karamouz et al. 2013; Wan et al. 2014; Glenis et al. 2013; DSM n.d.; FedTech et al. n.d.). Potential applications include directing and organizing rescue personnel, collecting and storing information on the disaster, communicating across a broad group of response organizations, directing evacuees and preparing resources in evacuation centers, and assessing risk in various areas and

under different scenarios through simulations.

The design approach for the Open-Well is user focused. The requirements for the development of a prototype Open-WELL environment from were taken from stakeholders in the emergency flood response community. This group was surveyed to understand potential use cases and data needs with a goal to identify areas that were lacking in flood response. The surveys included more than 70 individuals and organizations where flood data is commonly to support situational awareness during flood events. These stakeholders included federal agencies (e.g., FEMA, United States Army Northern Command), state response organizations (e.g., North Carolina Emergency Management, Texas Department of Emergency Management), and local or other response organizations (e.g., Pacific Disaster Center). The following are general themes that emerged from these interactions:

- Stakeholders utilize many formats of geospatial data, including raster and vector data products. Some stakeholders utilize the data to support visualizations, while other stakeholders use the data to perform subsequent geospatial analyses.
- Most stakeholders would like to have access to webservices that can be readily ingested into their platforms and workflows. However, this does not mean that raw geospatial data is not of interest. Many stakeholders require access to this data for their tools and analyses, such as damage estimation.
- Many stakeholders express desire to have access to past events for various activities. This includes claim validation, model performance enhancements, and planning for future activities.
- There is significant interest among stakeholders to have a technology that facilitates integration of multiple models. A common refrain is that more than one model creates confusion, but a recognition that multiple models could be of value.

2.2 Requirement for an Open-WELL Multi-Model Approach

We envision a future where there are multiple models providing rapid, near real-time predictive flood content. As such, there is the potential to create confusion amongst the end users and confound the ability to make decisions. A multi-model approach has benefits in flood response, but it requires research on optimal approaches to integrating, analyzing, interpreting, and visualizing output from multiple models. As part of the Open-WELL concept, we investigated methods that can be employed to facilitate the integration and interpretation of multiple datasets. As an initial effort, we explored simple methods that can be used to quantitatively compare multiple models and understand the challenges that must be overcome to facilitate a future multi-model ensemble framework for flood response.

A useful approach to multi-model flood prediction is to understand the agreement between two or more models. Flood extent comparison between various model outputs can be measured using the Critical Success Index (CSI), ranging from 0 to 1. The matrix shown in Figure 1 and the equation 1 show how models are compared using the CSI method. Existing water bodies are excluded from the calculations to focus the

analytics on floodplain impacts. Due to variation between model geographic extents, comparisons need to be confined where extents overlap.

Model1 \ Model2	Wet	Dry
Wet	WW	WD
Dry	DW	DD

Fig. 1: *Critical Success Index (CSI) Determination Matrix*

$$CSI = \frac{WW}{WW + DW + WD}$$

Where WW is Wet-Wet coincidence, WD is Wet-Dry coincidence, DW is Dry-Wet coincidence, and DD is dry-dry coincidence.

To demonstrate utility of an agreement metric, we use Hurricane Cristobal as a case study in which we compare the RIFT and HEC-RAS 2D model output developed on June 8, 2020 (Figure 2). The RIFT model defined its simulation domain based on the hydrologic unit code (HUC) 4 and the HEC-RAS 2D model used several irregular domains. Using the CSI methodology, the two models produce an index of 0.54 over HUC4 region 0807.

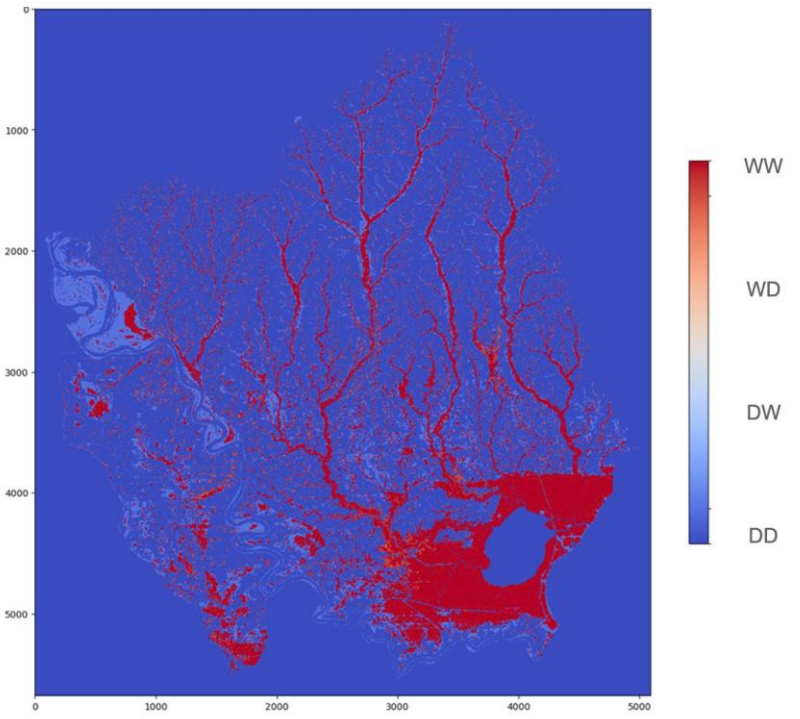


Fig. 2: *CSI Model Comparison between RIFT & HEC-RAS 2D (Hurricane Cristobal 6/8/2020)*

The CSI matrix for these two models is focused on areas where either model predicts the presence of water. The models diverge the most in the western portion of the modeled domain and this rapid comparison provided by the Open-WELL will enable collaboration between modeling teams and users on understanding the reasons for and implications of those differences.

Depth metrics also provide insight into model behavior. The Open-WELL can generate statistics readily between the two raster datasets. As depths between the two models are statistically compared, understanding variation will be key to building understanding of the differences of model output. Table 1 lists metrics to help quantify the variation between RIFT and the HEC-RAS 2D model output for Hurricane Cristobal.

Table 1. Depth Metrics (ft) between RIFT & HEC-RAS 2D

Metric	Value
Mean Deviation	-0.74
Mean Absolute Deviation	1.25
RMSD	1.85

Additionally, the Open-WELL enables comparison between different depth bins based on areal extents from each model as shown in Figure 3. This provides a visual indication where depths are being over or underrepresented in one model versus another.

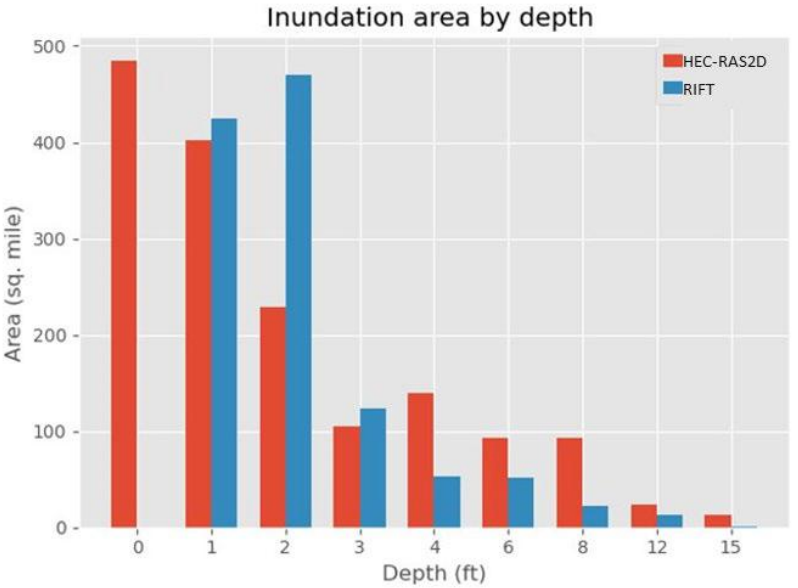


Fig. 3: *Inundation Area Comparison (RIFT & HEC-RAS 2D, Hurricane Cristobal)*

Disagreement between models is expected and should not be considered a fault of either the specific model or modeler. Not understanding model differences and not having a consistent mechanism for quickly recognizing and discussing the implications of the differences is the greater challenge. Models can differ due to choices made on model resolution, simulation domain, and model parameters and forcing information.

Choice in model resolution may depend on a number of factors. For example, for real-time events, such as a hurricane, large geographic extents may be required to fully capture potential areas at risk of flooding. In these cases, modelers may choose to develop simulations that are lower resolution in an effort to develop timely information for decision making. It is also recognized that not all flood models utilize the same physics or computational resources, thus this also impacts decisions relative to resolution and timeliness of simulations. On the other hand, simulations conducted during non-event time periods for planning purposes do not have such time constraints and may benefit from longer-running, high-resolution simulations. Given these considerations, and in the context of event-driven multi-model data integration, it is important that statistical analyses of data consider approaches to compare multi-

resolution data.

Simulation domain agreement is another notable challenge in multi-model comparison. As seen in Figure 4, the two models used during Hurricane Sally had limited simulation domain intersection. While there are reasons for simulations varying to such degree (e.g., request to include scenarios within adjacent basins), direct comparison has the potential to result in a very low agreement between predictions. In cases where there is variation in domains, careful attention must be given to appropriate one-to-one comparisons and include factors such as metainformation around simulations in addition to simple geographic domain considerations. Where domain definitions are missing, it is challenging to distinguish between domain and flood prediction mismatch in automatic data analysis.

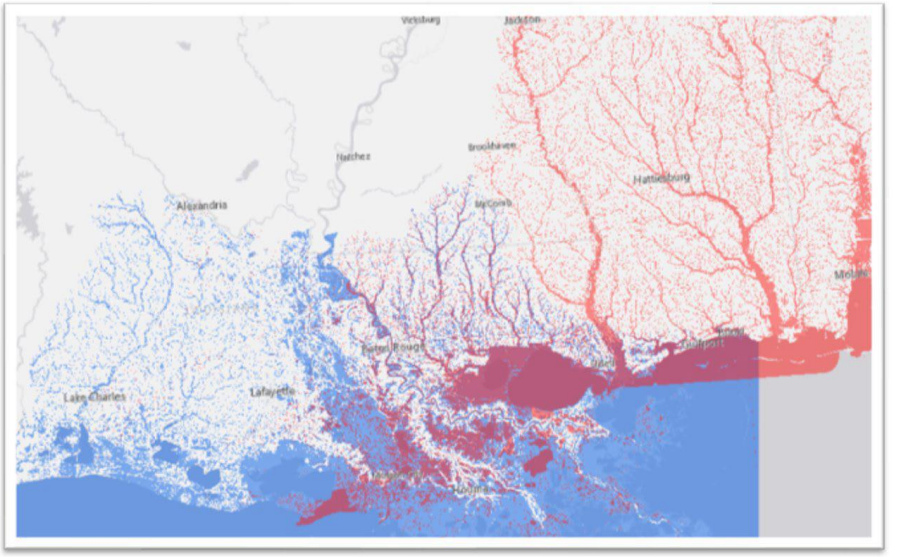


Fig. 4. *Hurricane Sally Domain Comparison- RIFT (Red) and (Blue)*

Finally, flood simulation models vary in parameters available (e.g., infiltration losses, roughness selections), forcing data (e.g., precipitation forecasts), and setup amongst the institutions conducting simulations; this can lead to complication of automatic data analyses. Model inputs, such as rainfall forecasts versus rainfall assumptions (or scenarios), can result in very different simulation results. Additionally, not all models include all aspects of flooding. For example, some models focus on fluvial flooding and ignore pluvial and coastal and storm surge flooding. Other models may include all aspects of flooding. To this end, it is important to establish requirements for metainformation and documentation such that proper evaluation of multi-model members can be completed.

The Open-WELL was constructed to address many of these challenges. The prototype Open-Well application is a fully customized, data-driven, single-page

application (SPA) with progressive web application (PWA) functionality. The client component was developed using React API, a lightweight, highly abstract, and modular framework. The backend component was built using predominantly serverless functions within AWS layered on top of a multitude of data and data storage combinations. Extensive effort was taken to streamline and simplify the user interface while also optimizing architecture and configuration for the backend for maximum efficiency and optimal response time.

3. Open-WELL Technology Prototype

3.1 Open-WELL Architecture

Considering both requirements and use cases, we developed a vision for the Open-WELL that is based on open geospatial consortium (OGC) compliant services while maintaining efficiency for use in large-scale flood events. The Open-WELL provides an efficient approach to collect, store, and visualize data from multiple entities, in addition to making the data available in web-based or desktop-based applications for end-user analyses. The Open-WELL is constructed to ingest any number of datasets, but primarily focus on the most commonly used flood parameters: depth, extent, and the velocity of flood waters. Figure 5 depicts the architecture of the Open-WELL. The Open-WELL is an adaptation of the WELL architecture that allows for third-party uploads in addition to serving and visualizing geospatial flood data.

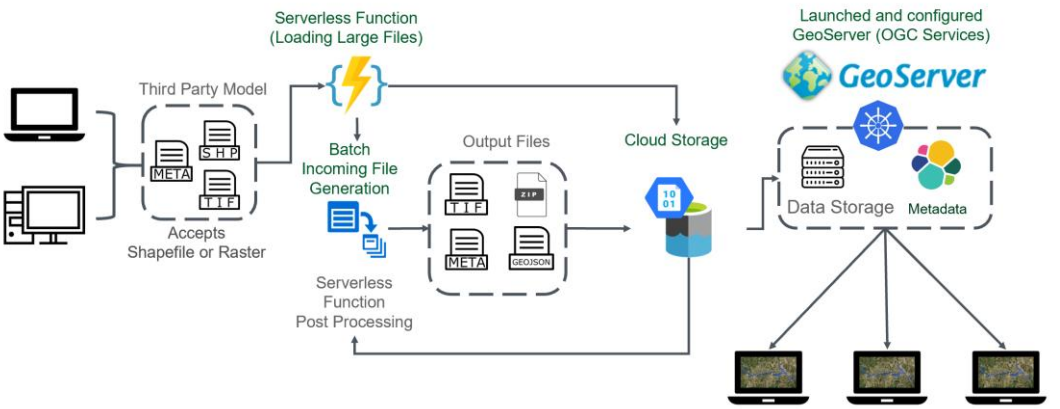


Fig. 5: *Open-WELL architecture for integration, storage, and visualization of multiple models for multiple users*

This cloud-based architecture allows for utilization of serverless technologies where possible. Serverless technologies are intended to take advantage of the scalable nature of cloud computing and dynamically allow services to be stood up or retired in a "pay as

you go" concept, as opposed to having dedicated servers constantly provisioned. This reduces deployment costs while enabling rapid technology innovation and utilization. The Open-WELL architecture is prototyped using AWS technologies including Lambda Functions, S3 buckets, and Geoserver. The architecture of the Open-WELL prototype can be described as three distinct processes. These include 1) pipelines to import data, 2) pipelines and technologies to serve data to end users for both desktop and web-based applications, and 3) a user interface.

The ability to ingest third-party models is the entry point to the repository. Third-party models are considered predictive flood data from the flood response community and are active during major events. An example use case that has driven the development is ingestion of both PNNL RIFT model output and the US Army Corps of Engineers (USACE) HEC-RAS2D output. In the future, it is expected that the number of participants and models will drastically increase. The general workflow is that an end user will be able to input file location (e.g., URL or local storage). Open-WELL will ingest that model and subsequently kick off a serverless function to move the file into a location before possible filename collisions could occur. To ensure standardization of data and OGC compliance, a post processing pipeline is triggered to convert file type, coordinate system alignment, raster resampling for consistency in resolution, and statistical comparisons (described later) through the use of Docker containers and set up as serverless functions. Once these are completed, metadata and appropriate files will be stored in the final repository and available for other services, such as indexing for search or visualization through geospatial technologies.

The right side of Figure 1 shows the portion of the Open-WELL technology focused on the creation of geospatial services that can be ingested into current and emerging web-based and desktop-based applications. The WELL technology used geojson to visualize dam-break and river flood data. This vector-based format was an efficient solution for smaller datasets and also provided data interaction options for the end user without having significant impacts on latency. However, testing of use-cases outlined herein have indicated that geojson formats are non-performant when representing larger flood extent models, such as large-scale pluvial and fluvial events. This is largely due to having too many polygonal vertices in the output datasets created during typical raster to vector conversion. Raster-based datasets have advantage over vector-based datasets relative to visualization of large geospatial datasets. To this end, we investigated the utilization of various tile servers which can cache raster-based geospatial datasets for rapid visualization. For the Open-WELL prototype, GeoServer was selected as the server of choice and installed on a virtual machine and configured with OGC WMTS endpoint layers for ingestion into other applications. Although we have chosen to use raster-based data types in the Open WELL, we maintain that it should remain an open question as to the appropriate data type and service to use, as there are positives and negatives to each type, and choice may depend on some of the ultimate objectives being pursued by different users of the system.

3.2 Open-WELL Implementation

The cloud-based architecture is primarily serverless with multiple copies of a virtual machine (VM) running a docker container that hosts a PostgreSQL database with PostGIS spatial extension and GeoServer1 open-source geospatial data server. The VM is set up through a load balancer for distributing resources. The application was built within a virtual private cloud (VPC), with data archived in a PostgreSQL server, Dynamo databases, and S3 unstructured data. Authentication is handled using AWS Cognito, Representational State Transfer (REST) functionality is developed using AWS Lambda functions and exposed via API Gateway. API Gateway is the central system for creating RESTful API for interacting with the client. Lambda is the scalable, serverless computing service that runs code in response to events and automatically manages the underlying computing resources. Underlying data resources include Dynamo semi-structured/noSQL data, PostgreSQL relational database system, and S3 unstructured data sources. A spatially enabled relational database management system, in conjunction with NoSQL, was used to leverage aspects of the application that are storage driven, normalized, relational, and good for online analytical processing.

All metadata related to events are stored in DynamoDB. This includes the list of events, storm inundation depths, storm footprints, storm time periods, modelers, and model types by entity. Strict enforcement of Primary Key and Sort Key were used throughout different Dynamo datasets keeping in line with best practices. Flood model output is stored in AWS S3 buckets which acts as the repository from which GeoServer accesses this information.

Users first introduction to the Open-WELL occurs via a landing page (https://open-well-staging.pnnl.gov/) that includes a disclaimer and a login page. After accepting the disclaimer, the user is directed to the login page. Username and password are initially held by a PNNL administrator, but users are promptly asked to change password upon first login. Users are then brought to a page that contains all events stored within the database. This includes both current and historical events (Figure 6). The left panel allows users to navigate available storms by name within a card that contains information such as number of forecasts available, number of institutions who provided data, the dates of the event, and the region it impacts. Each of those metadata are filterable using the search function of the predetermined filters at the top of the page. The page also allows users to navigate storms visually using the map-based functionality on the page.

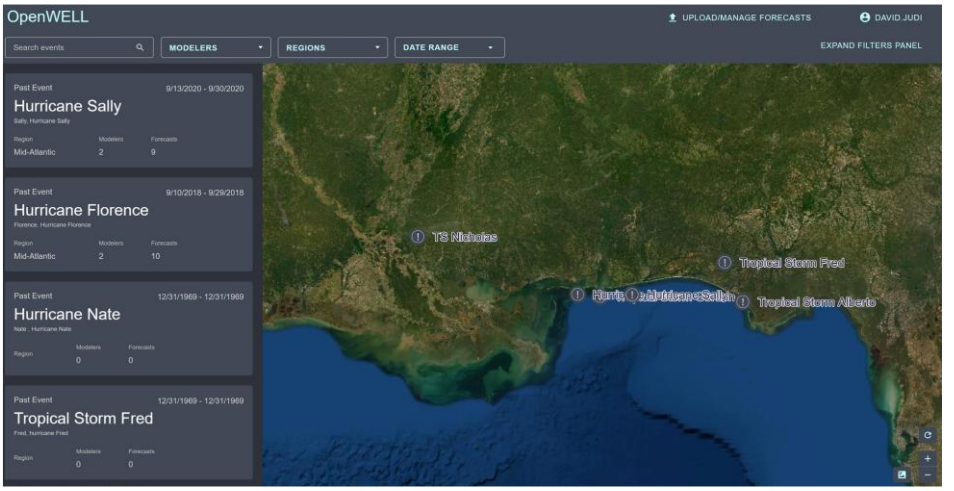


Fig. 6: *Open-WELL main data page with access to all data stored within the application*

Once a storm of interest has been identified, users can select the event either from the left panel or from the map. The initial view on the page is an empty map, a timeline of forecasts on the bottom panel, and a prompt for users to select a forecast from the timeline (Figure 7).



Fig. 7: *Open-WELL event view page*

The timeline contains all simulated data contained within the Open-WELL that has been tagged to the specific event. When data is uploaded into the WELL, a timestamp for the data is required. The timestamp is intended to represent the time in which the dataset provided is valid. For example, if a modeler conducts a simulation that covers a 5-day future period, the timeline panel indicates this with a circle to indicate start of period, followed by a horizontal line for the duration of the period. Each of the datasets (open circles followed by horizontal lines) are active links that the user can click to open the data. Users can select up to four datasets to view simultaneously and active datasets can be deactivated by simply clicking again on the timeline (Figure 8).

Once users select one or more events from the timeline, analytics become available

within the right panel. First, a histogram of depths is viewable at the top right. Each of the datasets are color coordinated (e.g., timeline timestamped data color matches depth distributions) for quick visual comparison of datasets. If two or more datasets have been selected by the user, the Open-WELL provides a similarity table (methods for similarity or CSI described in previous section, equation 1). The intent of this is to give users quick metrics on the similarity between datasets, which could be datasets from a single modeler but multiple forecasts, or multiple modelers.

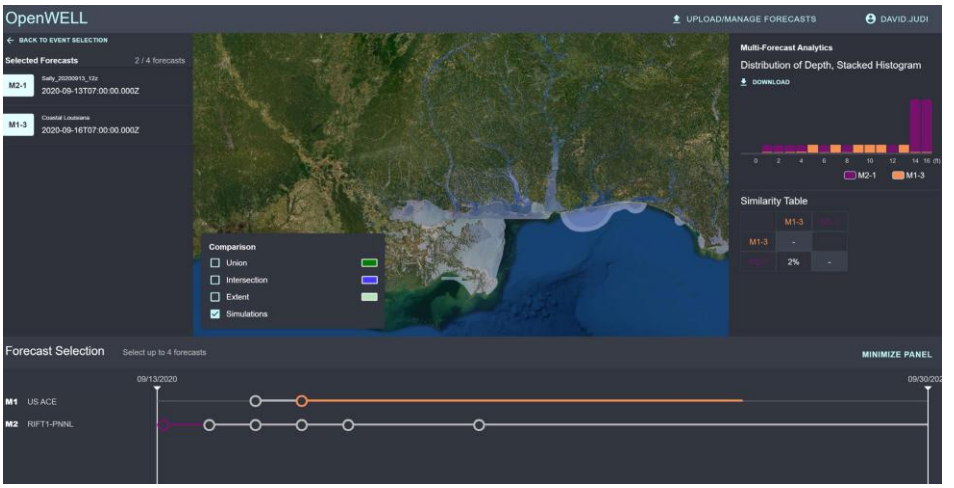


Fig. 8: *Open-WELL timeline is used to select specific forecast datasets to visualize and evaluate*

In addition to the analytics in the right panel, additional derivative datasets are available to help visualize differences in spatial extents between datasets. These visual comparisons are on a card available within the map viewer with options to select the union, intersection, and extent (Figure 9). The union provides a boundary that represents the entire envelope of selected simulations, whereas the intersection provides a dataset that only represents areas in which the selected data overlap. These derivative data are also color coded to match the timeline datasets.

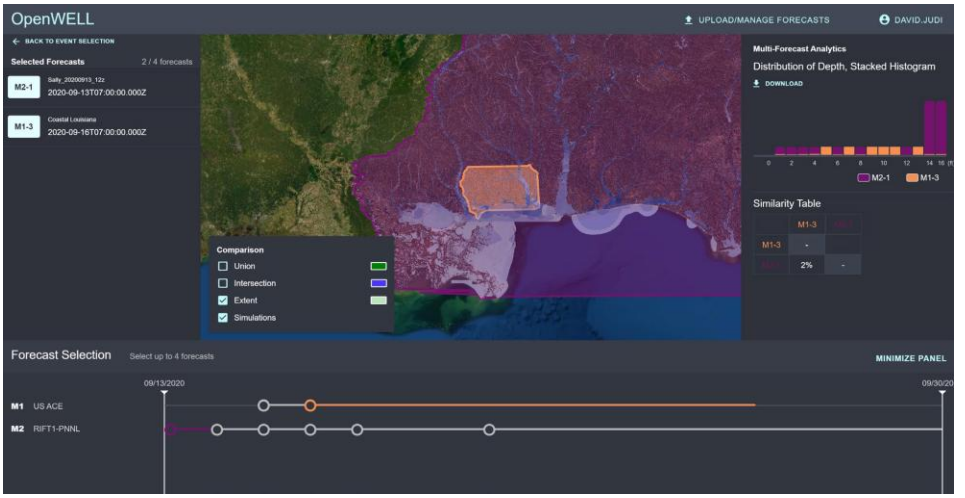


Fig. 9: *Open-WELL allows users to visualize the extents, union, and intersection between datasets*

The final feature on this page is the ability to view metadata from each of the timeline data in the left panel (Figure 10). This includes the runtime parameters (e.g., resolutions, text description) and various mechanisms to export the data. The user can select to download the data for local use, or the user can copy a URL of the WMS endpoint which then can be used to load data into other geospatial applications such as ArcGIS Online or desktop ArcMap.

The Open-WELL also allows users to upload data. This feature is available from any page and is located at the top of the page. When the user selects the upload link, the tool opens a panel on the right with the option for the user to drag and drop, or select from a local directory (Figure 11).

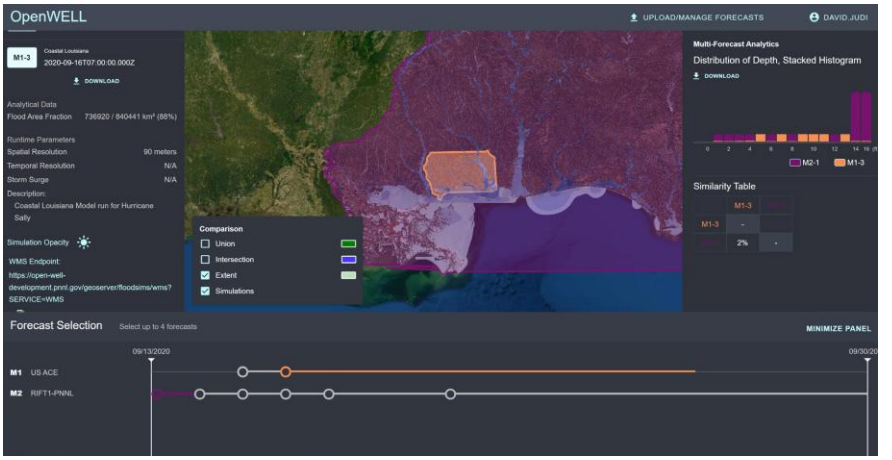


Fig. 10: *Open-WELL event viewer allows the users to inspect the metadata and download the data using multiple approaches.*

When a file has been loaded, a new set of required information is requested from the user. This includes the modeler name and the related event. Both of these parameters are selected from a drop-down menu that is populated by the manager of the Open-WELL. Additional information includes runtime parameters and other event descriptions.

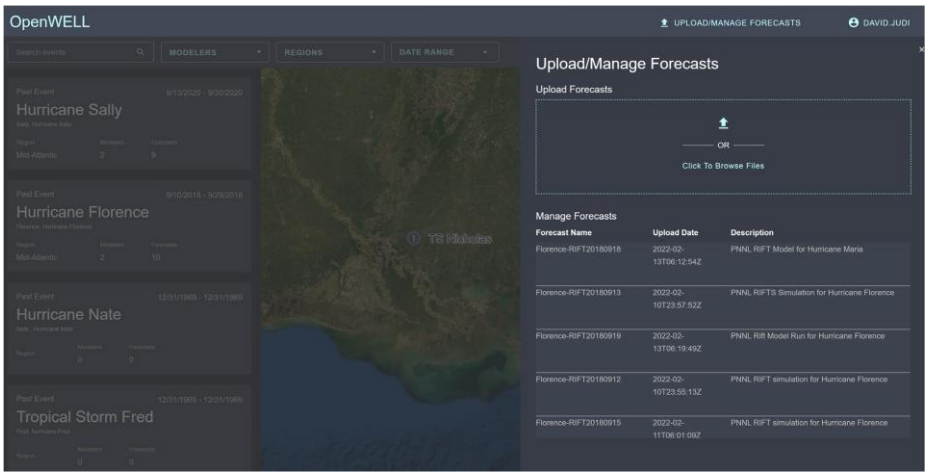


Fig. 11: *Open-WELL upload functionality*

4. Open-WELL Future Direction

PNNL has researched cloud-based technological advancements to enhance situational awareness in emergency response. To this end, PNNL has adapted the concept from an existing cloud-based technology, The WELL, to create a prototype community-based platform for model and data integration: the Open-WELL. The foundational objective of the Open-WELL is to enable collaboration across the flood response and recovery community by providing a place for models to be integrated. The future of the Open-WELL is based on a vision where multiple organizations will be able to develop predictive flood analytics and collaborate with each other on their improvement and application across a broad set of use cases. While trying to make sense of multiple predictive datasets can create confusion and confound decision-making processes in the interim, the Open-WELL architecture is intended to be a facilitator in this transition and transform a perceived community challenge into a strength. For example, we envision the Open-WELL as a facilitation technology that effectively allows a user to toggle between multiple models, understand the metadata and other information that is associated with each model, and collaborate with others on the ensemble of models that are available. For example, multiple models can be leveraged to provide new insights in the range of expected behavior in flood events through statistical comparisons, machine learning techniques, and probabilistic analyses based on ensemble model members. Perhaps more exciting, as we begin to build a repository of data from event response using technologies such as the Open-WELL, we will, for the first time, be able to systematically compare approaches and quantitively evaluate performance such that models and decision making can be improved.

5. Key Themes, Questions, and Additional Readings

5.1 Key themes

Key themes that emerged during the Open WELL project were:

- High-resolution flood modeling and simulation has shown great promise in supporting emergency responders.
- The operating environment is highly diverse including from on the ground first responders to state flood plain managers to federal emergency response officials. Each of these stakeholders requires flood and flood impact information that fits within their operational context while also still maintaining consistency across the diverse set of users and missions.
- Research, development, and documentation of the impact that cloud-based technology has on disaster response (e.g., floods, fire, earthquake) is largely qualitative or based on other types of crises. Significant potential for reducing response times, costs, and on-site technological needs is highlighted across both the academic and business literature, but few

studies exist to quantify the actual changes observed in disaster response due to cloud-based technology.
- We envision a future where there are multiple models providing rapid, near real-time predictive flood content. The Open-WELL architecture enables models to be cataloged and integrated allowing for an ensemble approach leveraging cloud-based technology similar to what is transpiring in the hurricane forecasting community.

5.2 Discussion questions

- What are some of the challenges in providing timely and accurate predictive flood analytics to the emergency response community?
- List some of the components of cloud-based technologies that are needed to support disaster response? Which are the most salient?
- What are some of the computational requirements needed to define areas at risk, areas to avoid, and areas requiring response and assistance during a flood event?
- What is a useful approach to multi-model flood prediction?
- List some of the factors to model resolution?
- What is a notable challenge in multi-model comparison?
- Flood simulation models vary in what common parameters which can lead to complication of automatic data analyses?
- Describe the key components of the Open Well prototype?

5.3 Additional Readings

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FedTech, Phil Goldstein Twitter Phil Goldstein is a web editor for, StateTech Besides keeping up with the latest in technology trends, he is also an avid lover of the New York Yankees, poetry, photography, traveling, and Escaping Humidity. n.d. “How the Cloud Helps FEMA Scale and Improve Disaster Response.” Technology Solutions That Drive Government. Accessed November 30, 2020. https://fedtechmagazine.com/article/2018/01/how-cloud-helps-fema-scale-and-improve-disaster-response.

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Section 3

Advancing Flood Resilience and Disaster Recovery

Flood events are not only momentary disasters; they are pivotal disruptions that expose systemic vulnerabilities and test the long-term resilience of communities. As climate change accelerates the frequency and intensity of such events, the stakes of recovery grow ever higher. Section 3 turns attention to the downstream side of the disaster cycle—examining how research, data, and modeling can inform smarter recovery, strategic mitigation, and equitable investment.

This section represents a shift in focus within the volume: from preparedness and response to resilience-building and recovery optimization. It explores the expanding frontier of flood science, impact analytics, and planning strategy, offering critical insights into how disaster recovery can evolve from reactive rebuilding to forward-looking adaptation. At its core is a simple but urgent premise: recovery is not just about returning to what was lost, it is an opportunity to reimagine what could be made stronger, safer, and fairer.

Yet traditional recovery approaches often fall short. Siloed planning, outdated modeling assumptions, and unequal access to post-disaster resources leave many communities locked in cycles of loss and marginalization. DHS S&T's flood resilience initiatives sought to break that cycle, investing in geospatial decision-support systems, remote sensing tools, and community-specific planning frameworks that help translate data into durable, inclusive outcomes.

The section opens with a technical exploration of extreme flood dynamics and atmospheric circulation patterns, offering new insight into how large-scale weather systems interact with geography to shape hazard exposure. This is followed by a study of urban flood modeling using high-resolution hydrodynamic simulations to identify and address risk concentrations in densely built environments. These methods are not theoretical exercises, they provide operational tools for planners, engineers, and emergency managers tasked with designing safer futures.

Further chapters examine the historical footprint of flood disasters through remote sensing and environmental forensics. By analyzing satellite imagery, land use change, and post-event terrain data, researchers reconstruct how floods have altered landscapes, displaced populations, and redefined development patterns. This long-view perspective is essential for understanding cumulative risk and identifying places in need of retreat, redesign, or resilience reinvestment.

A centerpiece of the section is a case study of Hurricanes Floyd and Matthew in North Carolina, which illustrates how repeated flooding stresses emergency systems and reveals the limitations of fragmented recovery policies. This analysis explores how post-disaster funding flows, mitigation decisions, and planning frameworks have shaped long-term trajectories—not just in North Carolina, but in hazard-prone communities nationwide. It offers a sobering yet instructive lens on recovery reform and investment prioritization.

The final chapter introduces FloodAdapt, a participatory decision-support platform piloted in Charleston, South Carolina. By integrating local knowledge, stakeholder input, and advanced modeling, FloodAdapt exemplifies a new generation of tools designed not just for accuracy, but for engagement. It signals a broader transition from top-down recovery to community-driven adaptation—where lived experience, equity, and scientific foresight converge to guide place-based planning.

Taken together, the chapters in Section 3 present a powerful synthesis of analytics, historical insight, and participatory design. They reveal that flood resilience is not merely about physical protection, it is about how we plan, how we recover, and how we choose to invest in the future. As flood risks intensify across the country, the approaches featured here offer a compelling blueprint for building forward—not back.

Understanding extreme floods, atmospheric circulation patterns and flood projection approaches

Katherine Schlef[31]

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Abstract

Floods in the United States cause billions in damages and are projected to continue to intensify under climate change and future extreme weather conditions. Extreme floods can be defined via a socially acceptable threshold, a statistical measure, as the flood of record, or as the probable maximum flood. Causative mechanisms can be classified as hydroclimatic and hydrologic, where the latter encompasses meteorology and catchment-state or the intrinsic catchment properties. Several studies have identified causative mechanisms for floods across the United States. Schlef, Moradkhani, and Lall (2019) identified four primary categories of atmospheric circulation patterns causing extreme floods across the United States. This new scientific research clearly shows certain regions have a dominant atmospheric circulation pattern that causes record floods. Comparing flood projection approaches under non-stationarity from climate-change, Schlef, François, and Brown 2021 show that compared to the default assumption of stationarity, the climate-informed and hydrologic simulation approaches provide added value while the trend-informed approach does not. This new scientific research indicates that causative mechanisms of extreme floods in the United States are relatively well understood but flood projection approaches under anthropogenic climate change have yet to be operationalized in guidance that explicitly accounts for uncertainty.

Keywords

Atmospheric rivers, circulation patterns, machine learning

1. Introduction

"Climate is what we expect, weather is what we get." (Attributed to Mark Twain 1887)[32]

Over the past 30 years, floods have caused nearly 200 billion dollars (2017$) in damages in the United States (Davenport, Burke, and Diffenbaugh 2021). As anthropogenic climate change continues, with on-going changes to extreme precipitation and temperatures, floods are also expected to intensify (USGCRP 2018).

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[32] Mark Twain (1887). This quote is commonly attributed to Twain. See Jeff Andreesen (2015). Climate Basics (E3151). November 15, 2015. Michigan State University. Accessible at https://www.canr.msu.edu/resources/climate_basics_e3151

Clearly then, flooding is a national challenge of high priority. In this context, this article highlights two studies that are outcomes of the Department of Homeland Security Flood Apex Program. The first study uses machine learning to identify atmospheric circulation patterns causing extreme floods in the United States (Schlef, Moradkhani, and Lall 2019). The second study compares various approaches to projecting floods under climate change (Schlef, François, and Brown 2021). This article focuses on riverine floods, recognizing that coastal flooding and flash floods are also of concern.

2. Defining an extreme flood

How an extreme (riverine) flood is defined depends on the context. One approach is to use a threshold set by government as socially-acceptable; for example, the National Flood Insurance Program has chosen the 100-year flood as the threshold to require flood insurance (FEMA 2011). Alternatively, a threshold could be based on a statistical measure (which may include a subjective choice by the analyst) such as return period, peaks-over-threshold, or an upper tail ratio (e.g., Smith et al. 2018; Schlef, Moradkhani, and Lall 2019). An extreme flood could be defined as the flood of record, which depends on the quality and length of the observational record, or as the probable maximum flood, which depends on the theoretical maximum rainfall and most flood-prone antecedent conditions. This article does not address the probable maximum flood for several reasons; the method of calculation is very different compared to the other extreme flood definitions, is it a somewhat controversial construct, and it is only used for the most critical cannot-fail situations since it corresponds roughly to at least the 10,000-year flood (François et al. 2019).

3. Types of causative mechanisms

The causative mechanisms of extreme riverine floods can be classified as hydroclimatic and hydrologic (Tarasova et al. 2019). Hydroclimatic refers to large-scale oceanic-atmospheric or synoptic atmospheric patterns, typically occurring in the months and weeks preceding an event. For example, the El Niño Southern Oscillation (ENSO) is a hydroclimatic mechanism. Hydrologic refers to the meteorology and catchment-state, typically occurring in the weeks and days preceding an event, or the intrinsic catchment properties. For example, the particular rainfall pattern such as an intense thunderstorm or hurricane is a meteorology mechanism; high antecedent soil moisture or abundant snowpack are catchment-state mechanisms; a mountainous versus relatively flat region is an intrinsic catchment property.

3.1 Studies on causative mechanisms.

Multiple studies have investigated various elements of the causative mechanisms of floods across the United States. For hydroclimatic mechanisms, Schlef et al. (2018) show that annual spring floods in the Ohio River basin and along the coastal south are positively correlated to ENSO while annual spring floods in the northeastern Midwest are negatively correlated to the Pacific/North American teleconnection pattern. For

hydrologic mechanisms, Smith et al. (2018) show that floods with a high upper tail ratio are caused by intense thunderstorms and occur in mountainous catchments. Also for hydrologic mechanisms, Berghuijs et al. (2016) show that annual floods are associated with one of four patterns: the largest precipitation event, the largest precipitation event in excess of soil moisture storage capacity, the largest series of precipitation events, or the largest snowmelt or rain-on-snow event. And lastly for hydrologic mechanisms, Schlef, Moradkhani, and Lall (2019), which is an outcome of the Flood Apex Program and will be discussed in more detail below, show that the flood of record and floods greater than the 10-year flood are associated with four broad categories of atmospheric circulation patterns. The above studies are at the scale of the United States; of course, there are many studies identifying causative mechanisms for a single flood event or for a given location. For an example of a location-specific study that evaluates all levels of causative mechanisms, see Carter and Steinschneider (2018), which focuses on the Lake Ontario region.

3.2. Atmospheric circulation patterns (highlight of study from the Flood Apex Program).

Schlef, Moradkhani, and Lall (2019) used a machine learning approach to analyze peaks over threshold floods and record floods at unimpaired gage locations within the Hydro-Climatic Data Network (HCDN) across the United States. The study found four primary categories of atmospheric circulation patterns:

- Tropical moisture exports, which include the “pineapple express” that occurs in winter on the West Coast and moisture transport from the Gulf of Mexico into the central United States that occurs throughout the year. Tropical moisture exports cause flooding across broad spatial regions and regularly cause extreme floods to occur outside the normal flood season. For example, a pineapple express event can cause a rain-on-snow flood event in January in the Sierra Nevada Mountains, when normally flooding would occur via snowmelt in late spring or early summer.
- Tropical cyclones, which include hurricanes on the Atlantic seaboard and the Gulf of Mexico as well as the North American Monsoon system in the Southeast. Tropical cyclones cause flooding across broad spatial regions and can cause extreme floods to occur multiple times in a single year. For example, on the Atlantic seaboard a hurricane may cause an extreme flood in the summer or fall after an atmospheric low or trough caused an extreme flood in the winter or spring.
- Atmospheric troughs or lows can cause heavy storms in all regions of the United States, occurring anytime from fall through spring, depending on the region.
- Melting snow – the absence of an atmospheric circulation pattern – occurs in late spring and early summer at high elevations in the Rocky Mountains.
- As part of the study, an interactive website was developed with detailed information for each record flood that was included in the analysis (https://kschlef.shinyapps.io/ExtremeFloods/).

3.3 Extension of atmospheric circulation study to impaired gages.

Figure 1 extends the results of Schlef, Moradkhani, and Lall (2019) to record floods at impaired gages. To create this figure, first, daily streamflow data was obtained from United States Geological Survey gages designated as part of the GAGES II network (Falcone 2011). Second, the date of the record flood for each GAGES II gage was identified and checked to find a match within plus or minus two days with a record flood for the HCDN gages from Schlef, Moradkhani, and Lall (2019). If there was a match, the atmospheric circulation pattern for the HCDN gage was assigned to the GAGES II gage; if there were multiple matches, the pattern with the greatest number of matches was chosen. Figure 1 shows that record floods rarely occur during the warm season on the West Coast, and rarely occur during the cold season in the Rocky Mountains and western Great Plains. Some regions have a clearly dominant atmospheric circulation pattern that causes record floods. Specifically, during the cold season there is the Pineapple Express and closely related Pacific Trough on the West Coast while during the warm season there is snowmelt in the Rocky Mountains, there is the Great Plains Jet from the Gulf of Mexico up to the Great Lakes region, and there is Atlantic Tropical Cyclones on the eastern seaboard. There are limitations to this analysis; only GAGES II record floods that match with the HCDN record floods are included and some record floods may be mislabeled (e.g., in the warm season, some record floods in the western Great Plains should likely be assigned to snowmelt rather than Great Plains Jet).

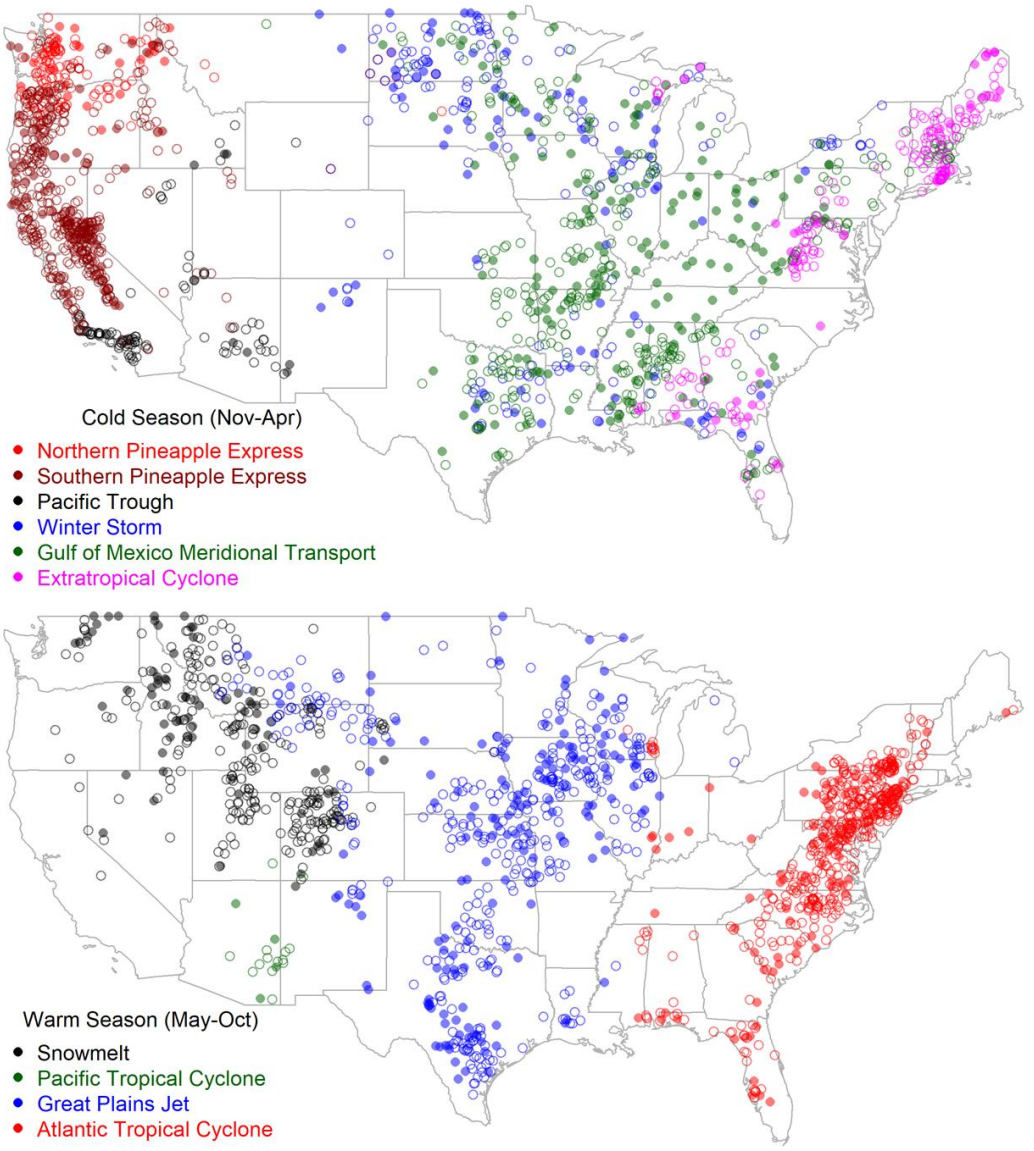


Fig. 1: *Results from Schlef, Moradkhani, and Lall (2019) for the atmospheric circulation patterns associated with record floods at unimpaired HCDN gages (solid circles) and an extension of the results to GAGES II gages (open circles). Refer to Schlef, Moradkhani, and Lall (2019) for more details on the definitions and seasonality of the atmospheric circulation patterns.*

4. Flood projection approaches.

With an understanding of the causative mechanisms for extreme floods, the next logical step is to develop projections. Here, projections refer to flood estimates that extend multiple decades into the future and account for anthropogenic climate change; projections are different from forecasts which are short-term and account for current

weather patterns. Figure 2 shows the various approaches to flood projection that have been employed in academic studies. The approaches are described briefly below and discussed in detail in the review by François et al. (2019). The stationarity approach, which is the default assumption to-date, does not allow the distribution parameters to change in time. Assuming non-stationarity due to anthropogenic climate change, there is either the informed parameter or hydrologic simulation approaches. For the informed parameter approach, the distribution parameters are regressed on time or a hydroclimatic covariate where projections of the covariate are obtained from general circulation model (GCM) outputs. For the hydrologic simulation approach a hydrologic model is forced by projections of precipitation, temperature, and other hydroclimatic variables from GCM outputs; subsequently a stationary distribution is fitted to the modeled hydrologic timeseries. Non-stationarity approaches are associated with large uncertainty, computational complexity, and other challenges. Consequently, their use in governmental guidance has been limited to-date; see Wasko et al. (2021) for a compilation of guidance from various countries around the world. In the United States, guidance has not yet incorporated a recommendation of a quantitative approach (England et al. 2018), though the Army Corps of Engineers requires that a qualitative assessment of climate change threats be performed for hydrologic analyses associated with long-term planning (USACE 2018).

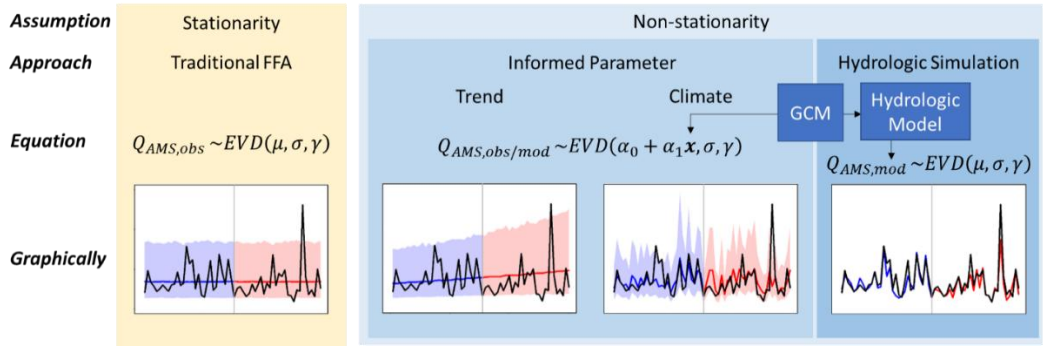


Fig. 2: *Approaches to flood projection for the annual maximum series discharge (Q_{AMS}). FFA is flood frequency analysis, EVD is extreme value distribution, GCM is general circulation model, and obs and mod are observed and modeled respectively. In the graphical depiction, blue is historic, red is projected, and black is the true value (shaded regions show uncertainty).*

4.1 Comparing flood projection approaches (highlight of study from the Flood Apex Program).

Schlef, François, and Brown (2021) performed a quantitative comparison of various flood projection approaches across a large set of hydro-climatologically diverse gages spread throughout the United States. The study focused on the 100-year flood and split the historic period into a calibration and validation period. Figures 3 and 4 summarize the main results from the study, which provide insight on key questions regarding the

performance of each projection approach:

- How biased is the magnitude of the projection estimates? (Figure 3, top panel) All the approaches had similar bias in the validation period except hydrologic simulation, which underestimated the 100-year flood
- Can the approach correctly project change? (Figure 3, bottom panel) By definition, the stationarity approach does not allow change. For the trend-informed approach, change was constrained and primarily positive. For the climate-informed approach (in the study, the covariate was precipitation), change was underestimated. The hydrologic simulation approach was able to match observed changes.

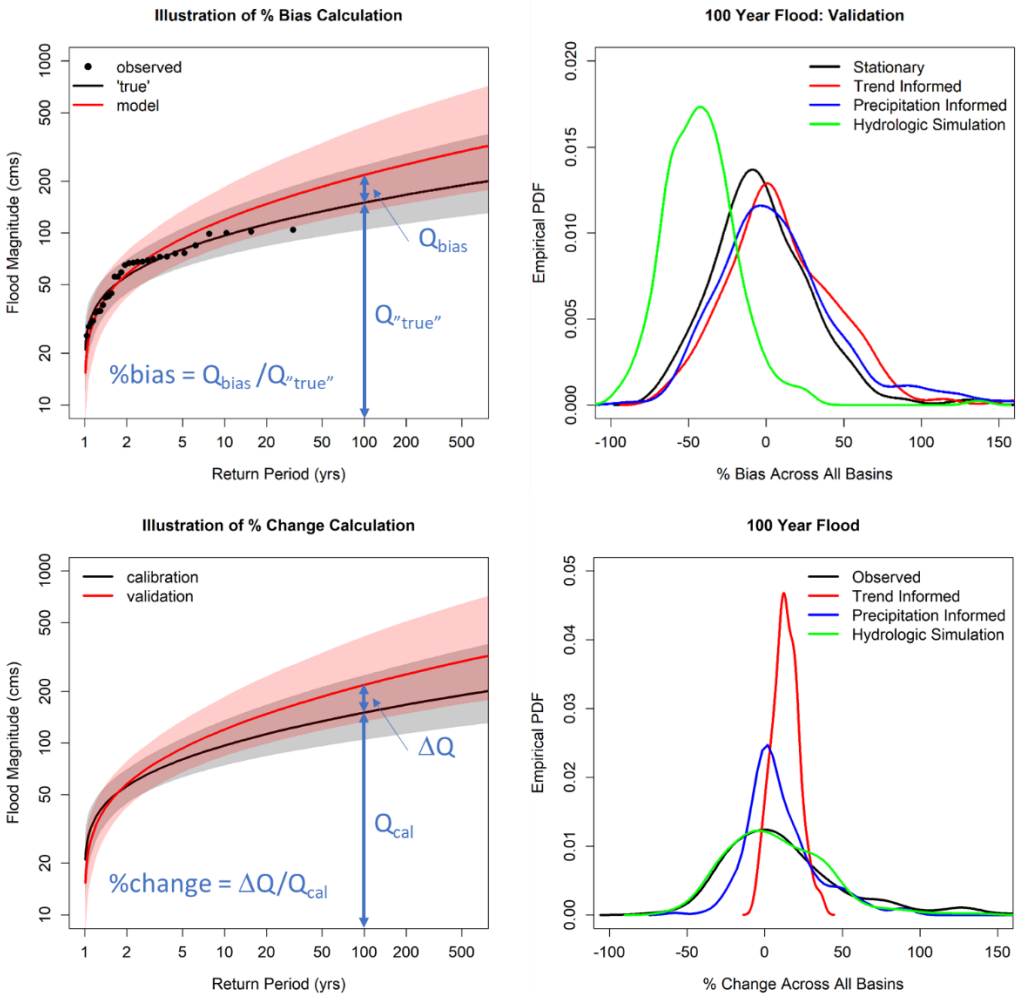


Fig. 3: *Results from Schlef, François, and Brown (2021) regarding bias in magnitude and projected change for various flood projection approaches. The left panel illustrates how the metric was calculated for each basin; the right panel shows the results across all basins. Here, the climate-informed and hydrologic simulation approaches are forced with observations.*

- How much additional bias and uncertainty are introduced when the precipitation-informed and hydrologic simulation approaches are forced with GCM outputs rather than observations? (Figure 4) The hydrologic simulation approach introduces much more additional bias and uncertainty than the precipitation-informed approach. Furthermore, for hydrologic simulation, the magnitude of the bias depends on the basin type, with large positive bias at high elevation basins.

The study concluded that in comparison to the assumption of stationarity, which is currently the default approach, the trend-informed approach does not provide added value. However, there is added value in the climate-informed approach for regional projections and in the hydrologic simulation approach for single basins depending on location.

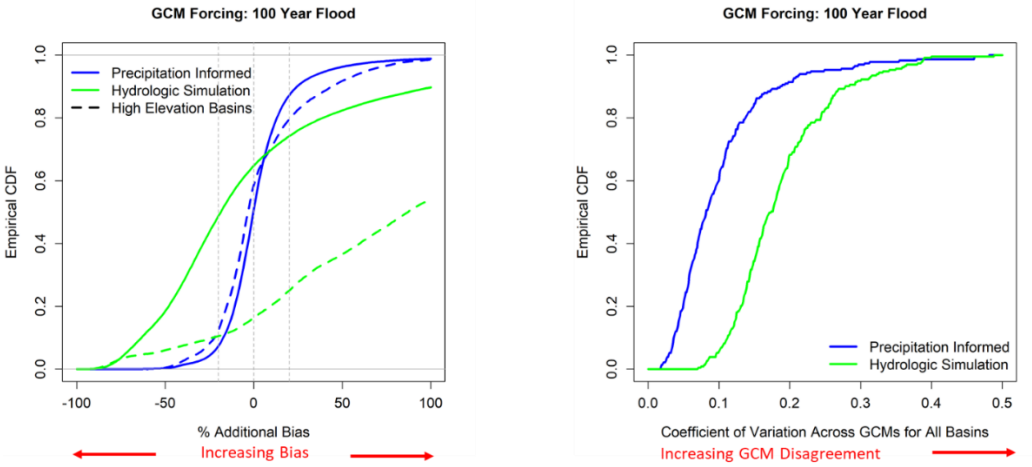


***Fig. 4**: Results from the Schlef, François, and Brown (2021) study for the additional bias and uncertainty introduced when the climate-informed and hydrologic simulation approaches are forced with GCM outputs as opposed to observations. Uncertainty is represented by the coefficient of variation across GCMs; refer to the study for details on how the metrics are calculated.*

5. Conclusion

Flooding and the associated damages are a national challenge in the United States. Some key aspects of addressing this challenge are understanding the causative mechanisms of extreme floods and being able to create projections of extreme floods under anthropogenic climate change. To-date, the causative mechanisms of extreme floods in the United States are relatively well understood at broad spatial and temporal scales and can be explicitly investigated for an individual event. This knowledge is valuable for improving forecasting models and for developing projection approaches that account for physical processes rather than being purely statistical in nature. While forecasting is difficult, the additional challenge with flood projections is the need for

projections of anthropogenic climate change, which are fraught with uncertainty. Consequently, despite the existence of several projection approaches, none have been operationalized in design guidance. Just as forecasts of flood events are useless if not acted upon (e.g., via early flood warning systems, disaster preparations, etc.), projections of flood events under anthropogenic climate change are useless if not incorporated into design paradigms that explicitly account for the uncertainty. This points to the need for design guidance to move beyond simplistic metrics based on average return period (e.g., the 100-year flood) to robustness-based decision methods informing adaptive design (François et al. 2019; Read and Vogel 2015).

6. Key Themes, Questions, and Additional Readings

6.1 Key Themes

The causative mechanisms of extreme floods in the United States are relatively well understood at broad spatial and temporal scales and can be explicitly investigated for an individual event.

Projection of extreme floods is still an on-going challenge due to the uncertainty associated with anthropogenic climate change; consequently, despite the existence of several projection approaches, none have been operationalized in design guidance.

6.2 Discussion Questions

- In what contexts might one definition of an extreme flood be more relevant than another? Which definition is relevant to your application or design question (and why)?
- Similarly, which scale or type of causative mechanism is of interest for your application or design question? How does this impact the type of analysis to be performed?
- How could the strengths of the climate-informed and hydrologic simulation approaches be leveraged into a joint (new) projection approach?
- What advancements (data, methods, policy, etc.) are needed such that flood projection approaches under anthropogenic climate change become operational and/or incorporated into federal guidance for design in the United States?

6.3 Additional Readings

- For more details on the two Flood Apex Program studies that were highlighted above, see Schlef, Moradkhani, and Lall (2019) and Schlef, François, and Brown (2021).
- For additional information about causative mechanisms for extreme floods across the United States, see Berghuijs et al. (2016) and Smith et al. (2018). For an example of identifying causative mechanisms at all scales for a given location, see Carter and Steinschneider (2018).
- For reviews on flood projection approaches under climate change see François et al. (2019) (specifically, discusses return period calculation and addressing

uncertainty) and Wasko et al. (2021) (specifically, compiles guidance from various countries).

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Characterizing Urban Flood Risk using Hydrodynamic Models

David Judi, Timothy McPherson, Michelle Li, Youcan Feng, and Cynthia Rakowski[33]
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Abstract

Urban flood risk is a combination of both pluvial and fluvial flooding. However, in many cases flood risk analyses only consider the fluvial component of flood risk. The objectives of this research were to develop an understanding of the types of storms (e.g., intensity, duration) in urban environments that result in pluvial flooding and flood damage, understand the role that urban storm sewer infrastructure plays in urban flood risk, and develop an understanding of the relative contribution of pluvial flooding on the overall flood risk. A case study was developed in Houston, TX to quantitatively examine the hydrologic characteristics and infrastructure consequences of the pluvial floods of various intensities and durations. A simple representation of urban storm sewer infrastructure based on design standards was implemented in hydrodynamic simulation to mimic the behavior of urban-area drainage systems. Through a series of simulations, it was observed that moderate duration storm events were most consequential while storm drainage systems largely mitigate damage from high frequency, short duration storm events and for low frequency, long duration storm events. Finally, it is also found that pluvial flood risk is not inconsequential relative to fluvial flood risk and that the flood risk area associated with each are not necessarily mutual.

Keywords:

Hydrodynamic, pluvial flooding, peak discharge

1. Introduction

"No place is safe from flooding. If it can rain, it can flood." (FEMA 2018)[34]

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[34] FEMA (2018). "All Texans are at risk." NR209 - Press Release on May 8, 2018. Accessible from the web at: https://www.fema.gov/press-release/20210318/all-texans-are-risk-floods

Urban environments are at the confluence of population, infrastructure, and economic activity and are particularly vulnerable to hydrologic events (Chang and Franczyk, 2008). More than 50% of the world's population reside in cities, and this is expected to increase by 2.5 billion by 2050 (UN, 2018). Eighty-six percent of the US population will reside in metropolitan areas at that point in time. Many urban environments throughout the world are located near water bodies and flooding can result in wide-spread disruption of critical physical, social, and institutional systems (Cho et al. 2017). Flooding in urban environments can occur anywhere and risk is not limited to locations near river or coastal bodies of water. In fact, flooding in urban environments can originate from a multitude of flood types, including pluvial, fluvial, and coastal flooding. Pluvial flooding is commonly known as flooding related to direct rainfall accumulation and transport, amplified by impervious surfaces in developed areas (Jha et al., 2012) and exceeding the capacity of designed storm water infrastructure. Hammond et al. (2015) more succinctly defined pluvial flooding as a result of urban drainage that is inadequate with respect to the rainfall of an urban area. In contrast, fluvial flooding generally refers to floods that originate from river systems when the water levels exceed the capacity of the rivers and expands into floodplain regions, potentially exceeding the capacity of flood control infrastructure (e.g., levees and stormwater). A consistent concern is that flood risk in urban environments will not only continue but also increase in the future under climate forcing. There are multiple contributing factors that drive this concern, which are primarily that the intensity and frequency of extreme rainfall and pluvial events is expected to increase in the future (Arnbjerg-Nielsen, 2006; Huntington, 2006; Trenberth, 2011) and that population is expected to continue to increase in urban environments (Hammond et al., 2015).

Methods and practices to assess flood resilience in the United States have traditionally focused on coastal and fluvial flooding and not pluvial flooding. Observations from actual flood events are suggesting that this focus should change. The National Academies recently stated that for counties that included Chicago and Houston, the average flood damage is over $200 million per year and note that true estimates of flood damage are likely much higher when accounting for pluvial flooding that results in uninsured losses, business disruption, and social disruption (NASEM, 2019). Other reports on flood events have highlighted the impact of pluvial flooding in urban environments. For example, heavy rainfall events in 2000 in the UK resulted in prolonged, extensive, and repeated flooding in locations not normally considered to have flood risk resulting in extensive property damage, 83% of which were outside traditional fluvial or coastal floodplains (Dawson et al., 2008). In the United States, the State of Illinois Department of Natural Resources evaluated the extent, cost, prevalence, and policies related to urban flooding in Illinois (Winters et al., 2015). Between 2007 and 2014, more than $2.3 billion in documented damages with most of those as private claims and over 90% of the urban flooding damage claims were outside the mapped floodplain. Winters et al. (2015) also concluded that most flood claims occurred in older sections of urban communities where original storm sewer

infrastructure is inadequate to handle present pluvial runoff (e.g., urban intense rainfall).

Pluvial flooding has not historically been considered in resilience programs in the United States. Flood risk in the United States is only officially recognized through the National Flood Insurance Program (NFIP) directed by the Federal Emergency Management Agency (FEMA) which focuses on 100 and 500-year fluvial or coastal (Ferguson and Ashley, 2017; Wallace et al., 2016) risk. After studying urban flood risk in 4 metropolitan areas across the United States, the National Academies suggested a refocus of how we characterize flood risk and recommended that new methods be established to properly characterize urban flood risk (NASEM, 2019). This recommendation includes the development of approaches to capture pluvial flood risk through hydrologic or hydraulic models.

The quantification of such pluvial contribution to flood risk has not been well studied and there is not currently any existing database that identifies pluvial flood extents (Schanze, 2018). Urban pluvial flood risk is a result of many factors, several of which can be explained by an understanding of the urban hydrologic cycle, expressed as

$$\mathbf{q = p - i - d - e,} \qquad \mathbf{(1)}$$

where pluvial flooding runoff (q) is a direct result of proper accounting of the precipitation amount (p), infiltration losses (i), engineered subsurface drainage (d), and evapotranspiration losses (e). Urban flood models do not generally consider the complete urban hydrologic cycle and generally focus on the rainfall-runoff process (Sanders, 2017). Such simplifications are often made because of highly impervious nature of urban environments and the lack of readily-available drainage infrastructure data to represent in a modeling platform (Liu et al., 2015; Schubert and Sanders, 2012). The consequence of neglecting those losses on flood forecast and the impact analysis is unclear (Gabellani et al., 2008; Tyrna et al., 2018; Yu and Coulthard, 2015). Among the loss terms, drainage tends to be most effective for volume reduction in urban environments (Tyrna et al., 2018). Some estimates in the literature estimate that drainage networks could convey 22.7%-44.8% of total precipitation out of urban environments (Dupont and Mestayer, 2006). However, it is not currently clear for what frequency and magnitude of storm events drainage infrastructure is consistently designed for which creates challenges in understanding how drainage infrastructure can be generically considered in the urban hydrologic cycle from a flood risk perspective.

There have been approaches identified in the literature to represent urban drainage infrastructure in a modeling framework. For example, dynamic coupling with bi-directional interaction (e.g., sources and sinks) is usually accomplished by coupling a 1D pipe model (Mark et al., 2004) with a 2D overland surface model (Delelegn et al., 2011; Leandro et al., 2009; Leandro et al., 2011; Malekpour et al., 2015; Neal et al., 2009; Simões et al., 2015; Vojinovic et al., 2011). Alternatively, simulating the unidirectional flow interaction, i.e. from surface runoff to storm sewer, is often adopted due to its

simplicity. In this case, manholes are only treated sinks (Liu et al., 2015). Unidirectional coupling, however, does not account for blockage cases explicitly (e.g., debris, mud) or storm sewer surcharging during the extreme rainfall events (Tyrna et al., 2017).

Another approach to capturing urban storm sewer drainage capacity is based on the understanding of design standards. The urban drainage system is typically designed based on a threshold design storm, implying that storms greater than the threshold design storm would result in potential flood risk (Henonin et al., 2013). The design requirements are usually influenced by a common local or regional design standard (Fratini et al., 2012), such as 1-50 return years in the U.S. (ASCE, 1992; Federal Highway Administration, 2009), 3-10 return years in Germany (Tyrna et al., 2017). Insight into the standards can facilitate the development of a conceptual approach to generically model drainage capacity by assuming a constant drainage rate through the computational domain (Chen et al., 2009) and effectively included in the urban hydrologic cycle to understand effective pluvial runoff volumes (Tyrna et al., 2017).

There are arguments for neglecting urban drainage completely in order to capture the worst-case scenario accounting for the potential of operational failure of these systems. For example, it can be argued that not well maintained or malfunctioning systems are not capable of draining surface water (Apel et al., 2016; Dottori and Todini, 2013; Ghimire et al., 2013). It has been recognized that 50% of storm sewer floods in the U.K. are attributable to an exceedance of capacity, while the other 50% are associated with blockage and or otherwise non-functioning systems (Dawson et al., 2008). In other cases, it can be argued that the design carrying capacity is significantly less than the runoff generated during extreme events, and therefore the storm sewer can be ignored (El Kadi Abderrezzak et al., 2009).

The objectives of this study were to develop an understanding of the types of storms (e.g., intensity, duration) in urban environments that result in pluvial flooding and flood damage, understand the role that urban storm sewer infrastructure plays in urban flood risk, and develop an understanding of the relative contribution of pluvial flooding on the overall flood risk.

2. Methods

A method was devised to quantify the relative contribution of urban pluvial flooding on overall flood risk using a modeling and simulation approach. In general, the approach was to capture the influence of rain characteristics (frequency, duration, and intensity) on the hydrologic response of urban catchments using a hydrodynamic flood model to simulate a range of peak discharges relative to urban storm sewer design standards. To develop a baseline understanding of nation-wide storm sewer design, storm sewer design standards across the U.S. were collected and summarized. The infrastructure consequences, described as economic damage to structures, of pluvial flood risk was estimated and compared to that of the fluvial flood risk.

Five urban drainage catchments near the White Oak Bayou in northwest Houston, TX were selected as candidate areas to evaluate pluvial and fluvial flood risk (Figure 1)

(Table 1). Houston, in particular, was selected due to the propensity of urban flash flooding and a relatively high flood risk compared to other studies. The boundary of each drainage area was delineated by the city government (https://cohgis-mycity.opendata.arcgis.com/). The selected urban catchments are all located in a topographically flat area with a relative high density of structures. The Rapid Infrastructure Flood Tool (RIFT) (Judi et al., 2018), a 2D hydrodynamic model, was used to provide both the pluvial and fluvial flooding simulations. Each flooding simulation was run for a 5-day period using10-m digital elevation data (DEM) from the United States Geological Survey (USGS) 3D Elevation Program.

For pluvial simulations, the frequency, intensity, and duration of rainfall events were sampled from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 (Table 2). Rain depths extracted from the NOAA Atlas 14 were assumed to be uniformly distributed in both time and space. To get a flow measurement for the pluvial discharge of each catchment for each storm event, a cross section was selected near the outlet of each catchment.

The fluvial flood events were not simulated as rainfall-runoff events, but utilized an upstream boundary condition of flow to simulate the fluvial dynamics. The upstream boundary conditions were determined using historical gage data and sampling from a frequency distribution of the annual peak river discharge. In this case, the historic gage data was obtained from the nearest USGS stream gauge (ID: 08074020; Latitude: 29°52'14"N; Longitude: 95°28'49"W) located at the upstream reach of the studied drainage areas.

For each of the simulations, the infrastructure consequence or damage associated with the flood extent was determined. The damage of a parcel of property was estimated based on the peak flood depth and appropriate fragility curves. The maximum flood depth of all grid cells within the boundary of a property parcel was averaged. One foot (~0.3 m) freeboard was subtracted from the calculated flood depth to account for nominal elevation associated with building foundations. The damage of the property was then estimated by multiplying its land improvement value by the percentage of loss corresponding to the depth-damage fragility curves. Specifically, the land improvement value of each parcel was collected from the Harris County Appraisal District (http://pdata.hcad.org/index.html) and the percent damage was estimated from the fragility curves available in the HAZUS-MH Flood inventory database. The damages of all inundated properties were aggregated to generate a total summed damage associated with a particular storm event, expressed as

$$\boldsymbol{D = \sum_{g=1}^{n} (fc_{g,h} \times SV_g),}$$

where D is damage ($), g is grid number, n is the total number of the flooded grids, h is the flood depth, fcg,h is the percent of damage looked up from the fragility curves (%) corresponding to the flood depth h for the gth grid, and SVg is the structural value for the gth grid ($).The expected annual damage (EAD) was calculated as the total of the products of the average damage between two consecutive exceedance probabilities and the difference between the two corresponding probabilities, expressed as

$$EAD = \sum_{i=1}^{m}[\frac{D_{P_i}+D_{P_{i-1}}}{2} \times (P_i + P_{i-1})],$$

where i is the rank of the exceedance probability, m is the number of probability increments, D_(P_i) is the damage corresponding to the ith exceedance probability, D_(P_(i-1)) is the damage corresponding to the (i-1)th exceedance probability, Pi is the ith exceedance probability, and Pi-1 is the (i-1)th exceedance probability (FEMA, 2016; Tariq, 2013).

To develop generalizations regarding the urban drainage infrastructure, the drainage design standards of a total of 65 U.S. major cities were surveyed based on published documents and government websites. The duration and return year of the design storm adopted by each city were collected and recorded. Minor drainage systems that are in the subsurface were not explicitly represented in the flood simulations. However in an effort to utilize generalizations of urban drainage in flood modeling based on the survey results, an approach based on design-storm intensity (e.g., IDF curves) was developed to represent the removal capacity of subsurface storm sewer systems. Given that storm drains areas are assumed to be prevalent in the Houston, TX area, each grid cell within the catchment domain was assumed to able to drain the volume of storm runoff by a drainage rate equivalent to the intensity of the appropriate design storm, which in the case of Houston, TX is approximately a 2-year storm. Based on the design standard of Houston (Sreerama and Varshney, 2017), the intensity is a function of time of concentration, expressed as

$$I = \frac{1905.254}{(16.2+T_C)^{0.8315}},$$

where I is the intensity of the design storm (mm hr-1), and TC is the time of concentration (minute). The time of concentration can be estimated by equation 6 (Sreerama and Varshney, 2017):

$$T_C = 10(247.1A)^{0.1761} + 15,$$

where A is area (km2). In this simple implementation of the drainage infrastructure, the drainage rate is assumed to be equivalent to the design storm intensity. It is noted that the drainage rate imposed by the infrastructure representation was mass conserving. That is, when the volume of water in a grid cell is less than the volume of water that can be drained by the storm sewer infrastructure within the current time step, then only the available water volume was allowed to be removed. The major drainage systems such as roads were captured by the 10-m DEM and, therefore, implicitly represented in the flood simulations. Since neither the subsurface pipelines nor the drainage routing were actually modeled, the influence of storm drains on the peak discharge of the stream channel was not studied, while only their implications on the flood damage and risk are noted.

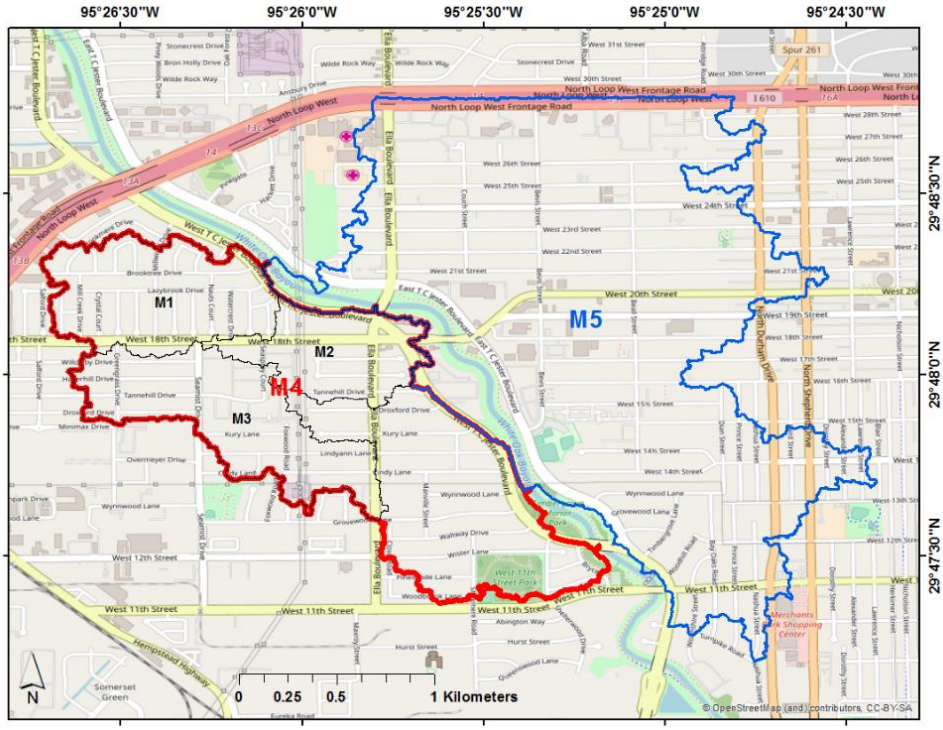


Fig. 1: *Five Houston-Area Catchments Used to Characterize Urban Flood Risk*

Table 1. Geographic and Socioeconomic Characteristics for Urban Catchments.

Catchment	Area (km^2)	Slope (degree)	Properties	Density (Properties/km^2)	Average Value ($)
M1	0.49	1.01	483	987	199 K
M2	0.31	0.96	304	983	356 K
M3	0.53	0.75	460	862	301 K
M4	2.07	0.94	1,704	822	204 K
M5	3.91	1.41	5,153	1,317	210 K

Table 2. *Frequency distribution of rain intensity (mm hour-1) obtained from NOAA Atlas 14 (Latitude: 30°3'59"N; Longitude: 93°41'21"W used as proxy since TX data wasn't available at time of simulations). The underlying heat-map colors visually represent magnitude of rainfall intensity.*

	Average recurrence interval (years)									
Duration	1	2	5	10	25	50	100	200	500	1000
5-min	177	201	239	270	314	344	378	411	454	485
10-min	130	147	175	198	229	253	277	300	331	355
15-min	106	120	142	161	186	205	225	244	269	289
30-min	79	89	106	119	139	155	172	188	211	229
60-min	53	60	71	81	97	109	123	137	158	175
2-hr	34	37	45	51	62	70	80	90	105	117
3-hr	25	28	34	40	48	56	64	73	86	97
6-hr	15	17	22	26	32	37	43	50	59	66
12-hr	9	10	13	16	21	24	28	32	39	44
24-hr	5	6	8	10	12	14	17	20	23	26

3. Results

3.1 Pluvial Peak Discharge

The peak discharge resulting from the pluvial simulations from all catchments are compared for various frequencies and durations (e.g., 2-yr, 5 min; 2-yr, 2-hr; 50-yr, 6-hr), as shown in Figure 2 and Table 3. As expected, the magnitude of measured peak discharge increases as storm frequency decreases for events of similar duration. That is, a 100-year, 24-hour storm event results in a smaller peak discharge in all watersheds than the peak discharge resulting from a 500-year, 24-hour event in the same watersheds. However, understanding the relationship between peak discharge, frequency of storm, and the duration of the storm is perhaps less intuitive. In this case study, the peak discharge for each watershed is sensitive to storm duration. For all watersheds in this study, the maximum peak discharge associated with the storm events occurred when simulating events of 2 to 6-hour in duration. For 4 of the 5 watersheds, the maximum peak discharges occurred consistently for events of 2 to 3 hours in duration, regardless of storm frequency.

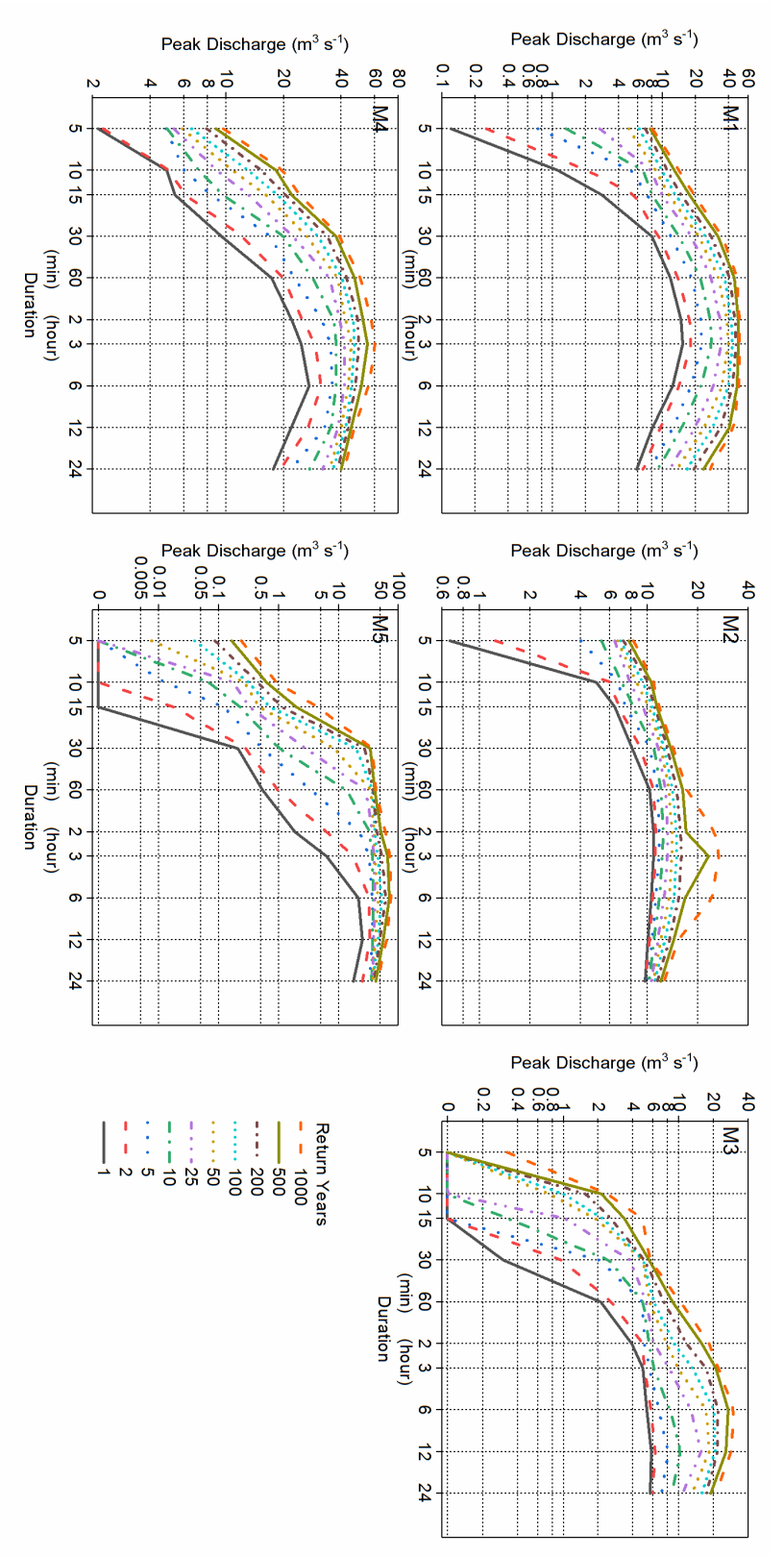


Fig. 2: The peak discharge of pluvial flooding at outlets of studied catchments

Table 3. Peak discharge (m3 s-1) of catchments (M1-M5) corresponding to rain events of various return years (1-1000) and durations (5-min to 24 hours). The heat-map color ramp, similar to that shown for the NOAA Atlas 14, visualizes the peak discharge intensity.

M1

	1	2	5	10	25	50	100	200	500	1000
5-min	0	0	1	1	3	5	6	7	8	8
10-min	1	2	5	7	8	9	10	11	13	14
15-min	3	6	7	8	10	12	13	15	18	20
30-min	8	9	12	14	18	22	25	28	32	35
60-min	12	14	19	22	28	33	37	41	46	48
2-hr	15	18	23	27	34	39	43	46	49	50
3-hr	15	18	23	28	34	40	43	47	49	51
6-hr	12	14	18	23	29	35	40	44	48	50
12-hr	8	10	13	15	20	24	29	34	41	44
24-hr	6	7	8	9	12	14	17	19	24	27

M2

	1	2	5	10	25	50	100	200	500	1000
5-min	1	1	4	5	6	7	7	7	8	8
10-min	5	6	7	7	8	9	9	10	11	11
15-min	6	7	7	8	10	10	11	11	12	12
30-min	8	9	10	11	12	12	13	13	14	14
60-min	10	11	12	12	13	14	14	15	16	17
2-hr	11	11	12	13	13	14	15	16	17	25
3-hr	11	11	12	12	13	14	15	16	23	27
6-hr	11	11	11	12	13	14	15	16	17	25
12-hr	10	10	11	11	12	12	13	14	15	15
24-hr	10	10	10	10	11	11	11	12	12	13

M3

	1	2	5	10	25	50	100	200	500	1000
5-min	0	0	0	0	0	0	0	0	0	0
10-min	0	0	0	0	0	1	1	2	2	2
15-min	0	0	0	0	1	2	2	3	3	5
30-min	0	1	2	3	4	5	5	5	6	6
60-min	2	3	5	5	5	6	6	8	9	10
2-hr	4	5	5	6	6	8	9	12	16	19
3-hr	5	5	6	6	8	10	13	17	21	22
6-hr	5	6	7	8	13	17	20	22	27	30
12-hr	6	6	8	11	16	19	21	22	26	29
24-hr	6	6	7	9	11	13	16	18	19	21

M4

	1	2	5	10	25	50	100	200	500	1000
5-min	2	2	5	5	5	6	7	8	9	10
10-min	5	5	6	7	9	11	13	15	18	20
15-min	5	6	8	10	13	16	19	21	22	24
30-min	9	12	17	20	22	27	30	34	38	39
60-min	17	20	23	28	35	38	41	43	47	51
2-hr	22	25	32	37	40	42	46	49	53	58
3-hr	25	29	35	38	42	45	47	50	55	61
6-hr	27	32	36	38	42	44	46	48	51	56
12-hr	22	27	33	36	39	40	43	44	45	47
24-hr	18	19	22	27	32	35	36	39	40	42

M5

	1	2	5	10	25	50	100	200	500	1000
5-min	0	0	0	0	0	0	0	0	0	0
10-min	0	0	0	0	0	0	0	0	1	1
15-min	0	0	0	0	0	0	1	1	2	5
30-min	0	0	1	1	3	9	20	27	34	37
60-min	1	1	4	14	29	35	38	39	41	43
2-hr	2	6	23	33	38	39	41	44	53	62
3-hr	6	18	33	37	39	41	46	53	68	74
6-hr	22	33	37	38	41	47	53	63	72	77
12-hr	25	34	37	38	39	42	47	50	57	65
24-hr	18	26	33	36	37	38	38	39	43	45

3.2 Damage and Risk

The potential economic damages caused by rain events of different durations and frequencies were compared (Figure 3, Table 4) to quantify pluvial-related flood damage. Similar to the previous findings relative to peak discharge, low frequency, high magnitude events are associated with larger economic damage. Also, the damage

associated with a return period event is sensitive to the duration of the storm event. In this case, the estimated damage across all return period events generally peaked between storm durations of 30 minutes and 3 hours, a shorter duration than peak discharge estimates. This measurable shift between the timing of peak discharge is attributed to two factors- 1) the immediacy (e.g., direct rainfall ponding) of flooding and associated damage in the catchment prior to rainfall-runoff accumulation and 2) and the resulting sensitivity to the relationship between storm duration and intensity.

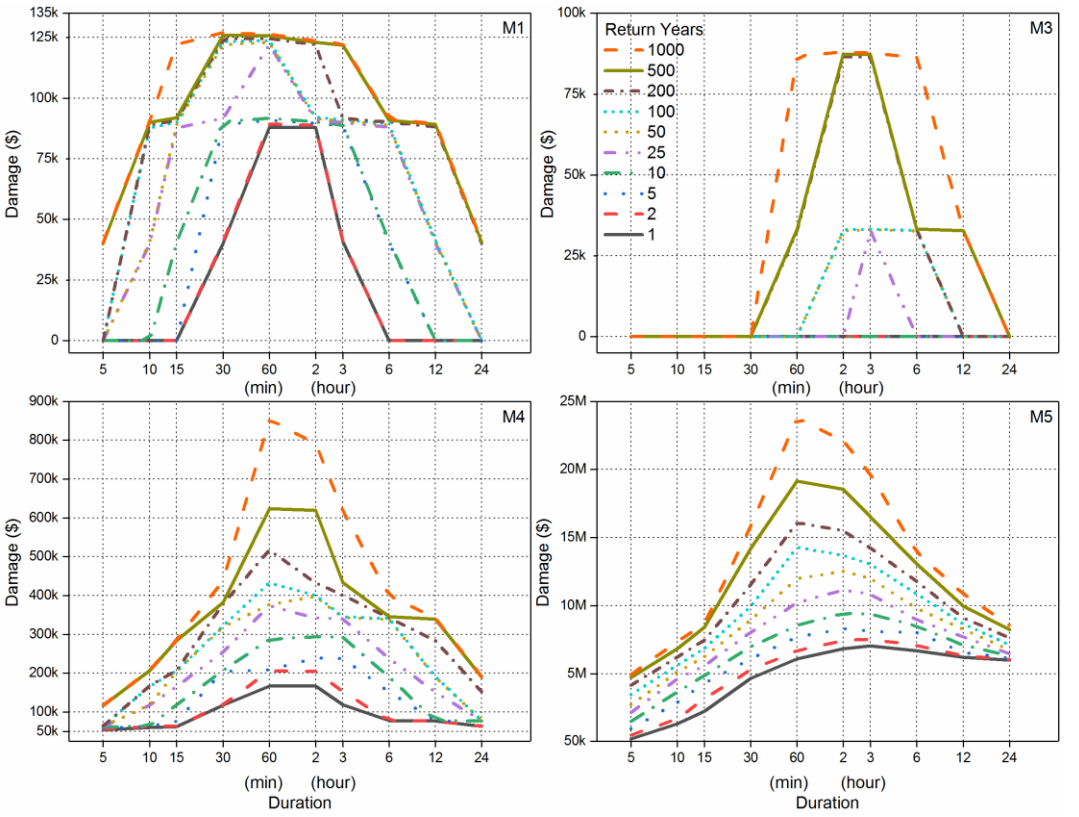


Fig. 3: *The economic damage of pluvial flooding. Note: catchment M2 does not have any damage and is not presented.*

Table 4. Flood damage ($K) of catchments (M1, M3, M4, and M5) corresponding to rain events of various return years (1-1000) and durations (5-min to 24 hours). The heat-map color ramp, similar to that shown for the NOAA Atlas 14, visualizes the damage intensity. Note: Catchment M2 that has no damage is not presented.

M1

	1	2	5	10	25	50	100	200	500	1000
5-min	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 40	$ 41
10-min	$ -	$ -	$ -	$ -	$ 40	$ 41	$ 88	$ 89	$ 90	$ 91
15-min	$ -	$ -	$ -	$ 40	$ 88	$ 89	$ 90	$ 91	$ 92	$ 122
30-min	$ 40	$ 41	$ 89	$ 90	$ 92	$ 122	$ 123	$ 124	$ 126	$ 127
60-min	$ 88	$ 89	$ 91	$ 92	$ 122	$ 123	$ 124	$ 125	$ 126	$ 126
2-hr	$ 88	$ 89	$ 90	$ 90	$ 91	$ 92	$ 92	$ 122	$ 123	$ 124
3-hr	$ 41	$ 41	$ 88	$ 89	$ 90	$ 91	$ 91	$ 92	$ 122	$ 122
6-hr	$ -	$ -	$ 40	$ 41	$ 88	$ 89	$ 90	$ 90	$ 91	$ 91
12-hr	$ -	$ -	$ -	$ -	$ 40	$ 41	$ 41	$ 88	$ 89	$ 90
24-hr	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 40	$ 41	$ 41

M3

	1	2	5	10	25	50	100	200	500	1000
5-min	-	-	-	-	-	-	-	-	-	-
10-min	-	-	-	-	-	-	-	-	-	-
15-min	-	-	-	-	-	-	-	-	-	-
30-min	-	-	-	-	-	-	-	-	-	-
60-min	-	-	-	-	-	-	-	33	33	87
2-hr	-	-	-	-	-	33	33	86	87	88
3-hr	-	-	-	-	33	33	33	87	87	88
6-hr	-	-	-	-	-	33	33	33	33	86
12-hr	-	-	-	-	-	-	-	-	33	33
24-hr	-	-	-	-	-	-	-	-	-	-

M4

	1	2	5	10	25	50	100	200	500	1000
5-min	54	56	59	62	63	63	64	64	117	118
10-min	61	62	63	64	117	119	166	167	206	208
15-min	63	63	77	118	166	205	206	208	284	286
30-min	117	119	205	207	255	319	322	378	382	438
60-min	167	206	208	288	373	377	433	517	624	854
2-hr	166	205	239	294	342	398	401	433	620	791
3-hr	119	153	238	293	341	343	345	401	433	618
6-hr	78	78	152	190	238	338	341	343	345	400
12-hr	77	77	78	78	152	190	191	284	339	341
24-hr	64	64	77	77	77	78	78	151	190	191

M5

	1	2	5	10	25	50	100	200	500	1000
5-min	231	503	952	1,498	2,167	2,725	3,470	4,169	4,718	4,944
10-min	1,337	1,682	2,895	3,669	4,619	5,112	5,642	6,215	6,845	7,361
15-min	2,241	3,160	4,315	4,868	5,593	6,252	6,861	7,466	8,427	8,713
30-min	4,659	5,297	6,103	7,000	8,049	8,969	9,942	11,538	14,212	15,843
60-min	6,108	6,702	7,716	8,541	10,216	11,994	14,288	16,103	19,155	23,813
2-hr	6,850	7,447	8,300	9,447	11,147	12,518	13,705	15,511	18,555	22,076
3-hr	7,057	7,543	8,132	9,393	10,845	11,995	13,029	14,239	16,530	19,640
6-hr	6,677	7,065	8,021	8,497	8,953	9,791	10,857	11,766	13,079	13,932
12-hr	6,200	6,325	6,568	7,097	7,729	8,262	8,672	9,112	9,983	10,872
24-hr	6,019	6,055	6,144	6,337	6,478	6,761	7,136	7,639	8,247	8,545

The worst-case pluvial flood damage within each storm return period, regardless of storm event duration, was further compared to the fluvial flood damage caused by the stream runoff of the same recurrence (Figure 4). In this comparison, only the 5, 10, 50, 100, 200, and 500 year return periods were considered due to availability of fluvial boundary condition data. In general, fluvial-driven flooding results in more extensive flood-related damage. This may be expected due to the volume of water collected in upstream portions of watersheds that are subsequently conveyed through urban environments. However, it is also observed that fluvial flooding does not impact all catchments equally and it is observed that those catchments without fluvial flood risk can still have pluvial flood risk.

The flood damages of various exceeding probabilities were aggregated as the expected annual damage (Table 5). For urban catchments M1 and M3, the pluvial flood risk turns out to have a larger expected annual damage than the fluvial expected annual damage.

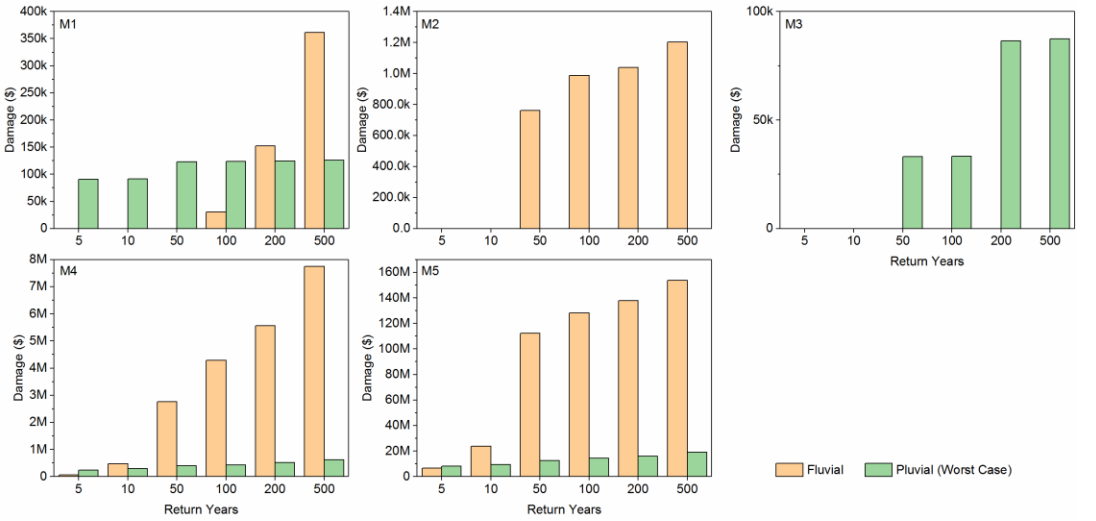


Fig. 4: *Economic damages of pluvial and fluvial flooding*

Table 5. Expected annual damage of fluvial and pluvial flood risk among five catchments.

	M1	M2	M3	M4	M5
Fluvial EAD ($/yr)	1,743	48,865	0	243,959	9,415,517
Pluvial EAD ($/yr)	20,080	0	2,301	63,227	2,048,000

(a) *EAD* = expected annual damage.

3.3 Impact of Storm Drains on Infrastructure

For storm sewer infrastructure design, design storms such as the NOAA Atlas 14 are used as the standard to guide the design of drainage systems, including the design of minor drainage infrastructure components such as storm drains. To get an overall sense of the design standards in the U.S., a total of 65 U.S. major cities were surveyed and the durations and return years of the specified design storms were identified (Figure 5). The majority of design standards require use of the 10-year, 5-minute storm. However, the design standard adopted by Houston, TX is the 2-year and 10-minute storm.

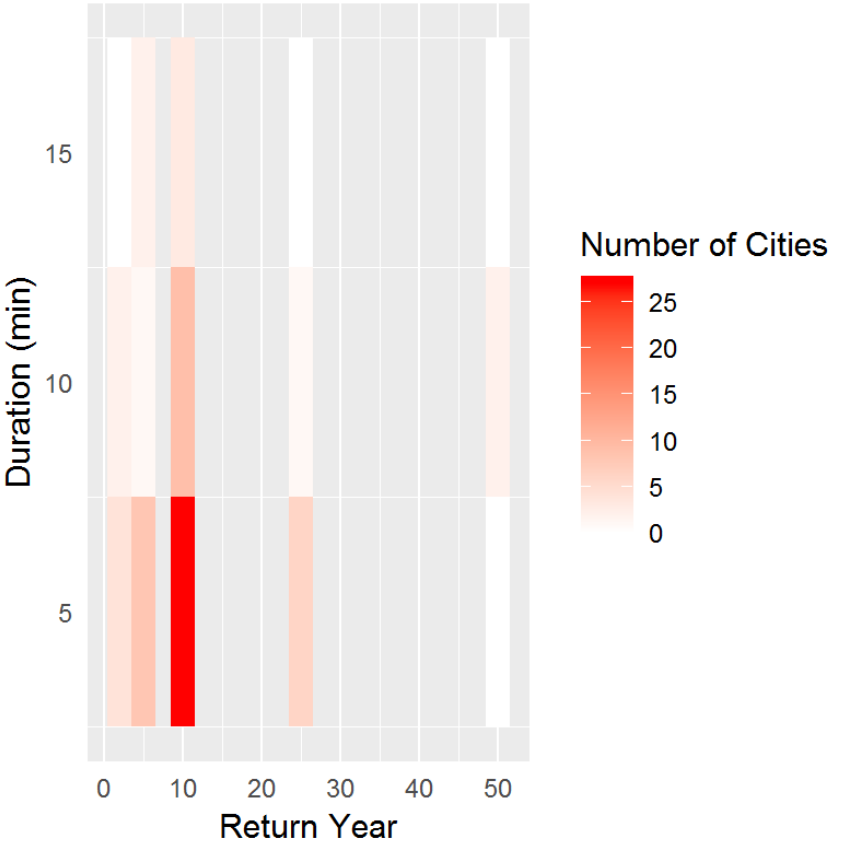


Fig. 5: *Histogram of the minimum standards of the design storms used by 65 U.S. cities.*

A first-order approximation of storm drain capacity was evaluated using a drainage rate equivalent to a 2-year, 10-minute design storm. As mentioned previously, the design standard requires the development of a rainfall intensity using the catchment time of concentration. For M1, M2, M3, M4, and M5, the intensity and, therefore, assumed drainage rate is 68, 70, 88, 62, and 69 mm/hr, respectively. All previous

simulations based on NOAA Atlas 14 design storms were re-simulated accounting for storm drain capacity and the subsequent damage was evaluated (Table 6).

Table 6. Percentage reductions in pluvial flood damage by storm sewer systems in catchments (M1, M3, M4, and M5) corresponding to rain events in the NOAA Atlas 14. Note: Catchment M2 that has no damage is not presented.

M1

	1	2	5	10	25	50	100	200	500	1000
5-min	-	-	-	-	-	-	-	-	100	100
10-min	-	-	-	-	100	100	100	100	100	56
15-min	-	-	-	100	100	100	100	100	56	28
30-min	100	100	100	100	100	100	67	28	28	4
60-min	100	100	100	100	100	100	67	27	27	3
2-hr	100	100	100	100	100	100	100	100	28	27
3-hr	100	100	100	100	100	100	100	100	100	66
6-hr	-	-	100	100	100	100	100	100	100	100
12-hr	-	-	-	-	100	100	100	100	100	100
24-hr	-	-	-	-	-	-	-	100	100	100

M3

	1	2	5	10	25	50	100	200	500	1000
5-min	-	-	-	-	-	-	-	-	-	-
10-min	-	-	-	-	-	-	-	-	-	-
15-min	-	-	-	-	-	-	-	-	-	-
30-min	-	-	-	-	-	-	-	-	-	-
60-min	-	-	-	-	-	-	-	100	100	100
2-hr	-	-	-	-	-	100	100	100	100	100
3-hr	-	-	-	-	100	100	100	100	100	100
6-hr	-	-	-	-	-	100	100	100	100	100
12-hr	-	-	-	-	-	-	-	-	100	100
24-hr	-	-	-	-	-	-	-	-	-	-

M4

	1	2	5	10	25	50	100	200	500	1000
5-min	100	100	100	100	100	100	100	100	78	55
10-min	100	100	100	100	100	57	67	65	70	50
15-min	100	100	100	100	69	73	71	50	58	42
30-min	100	100	100	75	76	67	48	45	26	34
60-min	100	100	100	100	84	69	53	51	49	56
2-hr	100	100	100	100	100	100	84	73	61	57
3-hr	100	100	100	100	100	100	100	84	73	62
6-hr	100	100	100	100	100	100	100	100	100	85
12-hr	100	100	100	100	100	100	100	100	100	100
24-hr	100	100	100	100	100	100	100	100	100	100

M5

	1	2	5	10	25	50	100	200	500	1000
5-min	100	100	100	100	97	98	98	98	94	82
10-min	100	100	100	98	98	89	81	69	66	64
15-min	100	100	99	99	90	80	70	68	63	55
30-min	100	100	99	92	74	70	62	49	45	41
60-min	100	100	100	99	80	74	59	52	47	49
2-hr	100	100	100	100	100	98	81	61	55	54
3-hr	100	100	100	100	100	100	100	81	56	57
6-hr	100	100	100	100	100	100	100	100	100	76
12-hr	100	100	100	100	100	100	100	100	100	100
24-hr	100	100	100	100	100	100	100	100	100	100

Considering storm drain capacity, the expected annual damage of pluvial flood risk was reduced by 100% for catchment M3. That is, all surface water for M3 simulations were effectively removed. The expected annual damage of catchment M1, M4 and M5 was reduced by 95%, 79%, and 85%, respectively. Overall, the representation of storm drainage was shown to have the capacity to effectively reduce the pluvial flood damage for most of the frequently-occurring rain events, especially considering short duration events and high frequency events. The storm drains, however, exhibit the least capacity to reduce pluvial flood damage for rare rain events with moderate rainfall durations ranging from 10 mins to 6 hours.

It is noted that the reduction of flood damage when incorporating drainage infrastructure is not necessarily a linear reduction. For example, while most simulations reveal a continuous decrease in damage reduction as storm return period increases and storm duration is held constant, the decrease is not linear and in some cases the decrease was not continuous. For example, M4 30-minute duration simulations continuously decreased in storm damage reduction, except for the 500-year to the 1000-year storms. In these events, the reduction was 26% and 34%, respectively. This does not mean that the 1000-year event resulted in less damage than

the 500-year event. It indicates that there is damage sensitivity to depth of flooding in the 1000-year and that a reduction in depth resulting from storm drain inclusion results in a larger relative contribution to damage reduction.

4. Discussion

4.1 Pluvial Contributions to Flood Risk

For this study, fluvial flooding is the most significant contributor to overall flood damage but pluvial flooding is a measurable component of urban flood risk and should not be neglected. Using peak discharge as a comparative metric, pluvial contributions of flooding were measured to be as much as 15% of the fluvial flow.

An interesting component of this study was a close evaluation of the relative contribution of storm duration and frequency of storms on pluvial peak discharge and pluvial flood damage in urban environments. For example, it is not necessarily intuitive to understand which storms from the NOAA Atlas 14 dataset are most consequential. It is obvious to suspect that lower frequency, higher magnitude storms are more consequential but the role that duration plays in impacting urban flood risk is not obvious. Inspection of the NOAA Atlas 14 tables (Table 2) could lead to a belief that the most consequential events to consider in risk assessments are low frequency, short duration events since these rainfall intensity rates are highest. In this study, for example, the 1000-year, 5-minute storm has an intensity of 485 mm hour-1, while the 1000-year 2-hour storm only has an intensity of 117 mm hour-1, potentially leading one to believe that the worst-case scenario is the former. What is demonstrated in the results is that rain volume, a function of duration, and intensity both influence the pluvial peak discharge. The hydrologic response of the urban catchments were most impacted by storm events with medium-range duration, which result in the highest peak discharge of pluvial floods. This response is due to a combined effect of urban catchment size, flow volume, and attenuation. For example, the short duration, intense events drop a significant amount of water in a very short amount of time. By the time water in the catchment begins to accumulate, the storm event has ended and the accumulated water begins to attenuate quickly. On the other hand, long duration storms have lower average intensities and while the storm continues over a long period of time, attenuation is not a significant factor but the storm event does not develop large volumetric rates.

There are two observations to make relative to this understanding. The first observation is relative to storm sewer infrastructure design. The survey of 65 U.S. cities shows that most U.S. cities target storm sewer system minor components (e.g., drains, pipes) to the 10-year storm and 5 minute duration. The peak flow rates measured by simulation for the 10-year, 5-minute storm in this study are in the 10th percentile of flow rates observed. When using peak flow as an indicator of storm sewer infrastructure ability to handle storm events, one would assume that the design standard fails to remove water from a significant number of storms. However, as we will evaluate later, the distributed nature of storm drain infrastructure produces a non-linear reduction in surface flow observed through the reduction in damage.

The second observation is the importance of moderate storm durations (e.g., 2 to 6 hours) when trying to understand events of significant consequence. For situational awareness, hydrodynamic models forced by precipitation forecasts can be used to develop estimates of flooding in urban environments. For instance, a hydrodynamic model may be used to provide situational awareness for a multi-day tropical storm event forced by multi-day estimates of rainfall accumulation. To capture the storm impact relative to flooding, a temporal distribution of rainfall is applied to the precipitation forecast for simulation. The findings in this study indicate that the intensity of rainfall over periods of 2-6 hours are important to capture if the desire is to capture urban area impacts where catchments are relatively small. Ignoring the potential for intense rainfall periods within long duration storm events has the potential to underestimate the flood risk.

4.2 Pluvial Flood Infrastructure Consequences

The economic damage indicated a non-linear relationship with rain duration (Figure 3). The greatest damages occur during the storm durations of 30 minutes to 3 hours. These durations represent a slight shift to shorter durations than those associated with peak flows (Figure 2 and Table 3). Although initially counter intuitive, the peak discharge tends to be more sensitive to storm volume, while damage is more sensitive to storm intensity. As a consideration to reducing flood damage in the immediacy of the storm (e.g., within the urban catchment where the rain occurs), quickly and efficiently removing the water from the surface into storm sewer conveyance systems is an effective strategy for reducing property damage. On the other hand, increasing the efficiency of volume reduction at the urban catchment scale has potential downstream impacts as a result of increased peak discharges. Storage-focused green infrastructures enhancing infiltration and evapotranspiration are a consideration to alleviate this issue.

As shown in this study, there is potential for flood risk that originates from events other than fluvial flooding. Intense rain events of moderate duration in urban environments that may not normally be considered as flood-prone areas do, in fact, have flood risk. Pluvial and fluvial floods do not necessarily occur coincidentally nor are the risk areas necessarily mutual, so consideration of flood risk estimates that consider only fluvial flooding has the potential to underestimate the true value of risk (Figure 4.1). Overall, the magnitude of pluvial flood damage tends to be less significant than that of fluvial flood damage. However, this study finds that the damage resulting from pluvial flooding can be larger than that of a fluvial flood for the same recurrence interval. For example, the damage in M1 is higher for several higher frequency pluvial events than for the same fluvial events. The repeated and expensive damages due to the frequent pluvial events leads to a higher expected annual damage. Ignoring the contribution of pluvial floods in a risk estimate, in this case, will undervalue the true flood risk.

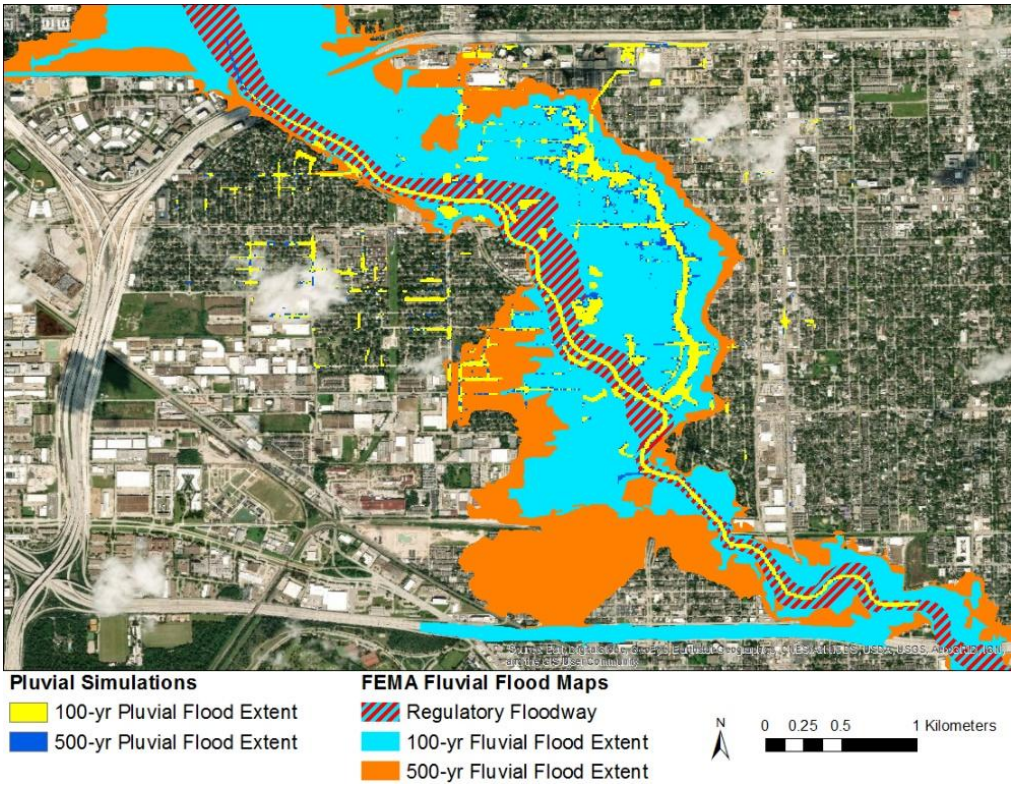


Fig. 6: *Inundation extents of the simulated pluvial flooding zones (area with depth less than 1-foot freeboard removed) and FEMA fluvial floodplains.*

4.3 Storm Sewer Impact on Urban Flood Risk

When including storm drains in hydrodynamic simulations, the damage due to pluvial flooding is effectively reduced especially for short and long-duration storms. The storm drains, however, have less impact on the medium-duration (10 mins to 6 hours), low-frequency storms, corresponding to the same storms that resulted in the most significant impact (Figure 3). There are limitations to this simplified representation that should be noted. Primarily, this study only considered the one-way interaction from the overland flow to the river, but did not model the reverse direction which is possible during wide area, extreme events (e.g., Hurricane Harvey). In addition, the removal of water from the hydrodynamic simulation was permanent rather than transporting the removed water to a receiving water body (e.g., river) to be conveyed downstream.

The contribution that the storm drain infrastructure had in reducing flood damages for storms beyond what may be intuitively inferred based on design storms is notable. The design standard used in this study was a 2-year event where duration was based on the time of concentration of the watershed, nominally 10 minutes. An assumption may be made the flood damage reduction only occurs for storms of lesser magnitude, but the results show a clear, non-linear contour of damage reduction for a range of storm

intensity and durations. This is primarily due to the distributed nature of storm drains and the immediacy of storm water removal prior to accumulation. As mentioned previously, this also provides justification for investment in localized green infrastructure to remove accumulated rain.

Ideally, storm sewer contributions to flood management would be represented by a dynamical coupling of a 2D overland inundation model with a 1D pipe model, where all conservation equations and the two-way interaction can be captured. In practice, however, such coupling is generally computational expensive and requires the detailed pipe information which is seldom available to the flood modelers. A simplified conceptual model mimicking the storm drains within the flood model can be still useful for baseline situational awareness and for estimating urban flood risk.

5.0 Conclusion

Urban flood risk is a combination of both pluvial and fluvial flooding. However, in many cases flood risk analyses only consider the fluvial component of flood risk. The objectives of this research were to develop an understanding of the types of storms (e.g., intensity, duration) in urban environments that result in pluvial flooding and flood damage, understand the role that urban storm sewer infrastructure plays in urban flood risk, and develop an understanding of the relative contribution of pluvial flooding on the overall flood risk. A case study was developed in Houston, TX to quantitatively examine the hydrologic characteristics and infrastructure consequences of the pluvial floods of various intensities and durations. A simple representation of urban storm sewer infrastructure based on design standards was implemented in hydrodynamic simulation to mimic the behavior of urban-area drainage systems. It was found that moderate duration storm events (2-6 hours) are most consequential in terms of peak flow and damage in urban environments. This provides future guidance on utilization of design-based storm events, such as those available in NOAA Atlas 14, relative to selection of duration of event in order to capture true flood risk.

6. Key Themes, Questions, and Additional Readings

6.1 Key themes

Key themes that emerged during Characterizing Urban Flood Risk using Hydrodynamic Models study were:

- Urban flood risk is a combination of both pluvial and fluvial flooding. Most current approaches to analysis only cover the fluvial dimensions of urban flooding.
- Floodplain and stormwater management systems are critical components toward addressing urban flood risk. Their operations are often siloed and have different standards of protection for risk management.
- The types of storms (e.g., intensity, duration) in urban environments that result in pluvial flooding and flood damage and the role that urban storm sewer

infrastructure plays in urban flood risk as well as the relative contribution of pluvial flooding on the overall flood risk is not well understood.
- This lack of understanding means that flood risk modeling tools are lacking and could be improved by incorporating hydrodynamic models.

6.2 Discussion questions

- What are the key challenges for floodplain and stormwater managers in urban environments?
- What are the key drivers of urban flood risk? And what are the limitations of current approaches to flood analysis?
- How do urban drainage systems differ from rural systems? How does this difference contribute to flood risk?
- What were the key observations from this research study on the effectiveness of urban-area drainage systems?
- This publication presented a use case for Houston, Tx. What use cases can you think of for the area where you live?

6.3 Additional Readings

- Rapid Infrastructure Flood Tool (RIFT) webpage. - https://open-rift-pnnl.hub.arcgis.com/. Accessed on February 21, 2023.
- PNNL Research Highlight (November 13, 2020) – "How Floods Start and Their Recent Trends". Accessible from the web at https://www.pnnl.gov/publications/how-floods-start-and-their-recent-trends.
- PNNL Research Highlight (September 12, 2017). "Flood Modeling Helps DHS During Busy Hurricane Season." Accessible from the web at https://www.pnnl.gov/news-media/pnnl-flood-modeling-helps-dhs-during-busy-hurricane-season.

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Understanding historical flood risk through remote sensing

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Abstract

The main objectives in mapping floods are to detect where damage has occurred, how much damage has occurred, and to predict where it may happen again. One approach is to conduct a Multi-temporal Satellite Image-based Flood Analysis (MSIFA) using satellite imagery collected over the course of decades for a target AOI (area of interest). Water is automatically extracted from each of the images. Then the water masks from all dates are stacked up and the number of times water has been observed in the masks for each pixel over time is calculated. Then the ratio of number of water observations to number of total observations (how many images with data cover the pixel) is calculated. If there have been no observations of water over the past couple of decades, then it is unlikely that flooding has occurred at that location. If 100% of the pixels are observed as water, then it is likely a persistent water feature such as a lake or river. But between 0 and 100%, water is observed intermittently, which can mean flooding. The results from a MSIFA were used to create a series of products, based on 35 years of Landsat imagery that include: Observed Flood Extent (OFE), New Construction at Risk of Flooding (NCRF), Flood Post New Construction (FPNC) and Dates of Detection (DoD) to support flood risk reduction and mitigation planning and investment.

Keywords

Satellite imagery, observed flood extent, risk reduction

1. Introduction

"The broad problem of flood-loss reduction is that the rate at which flood losses are being eliminated by construction of engineering or land-treatment works is of about the same magnitude as the rate at which new property is being subjected to damage." (Gilbert 1960)[37]

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[37] Gilbert White (1960). "Strategic Aspects of Urban Flood Plain Occupance." *Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers* 86 (HY2):89-102.

Historically, flooding has killed more people than any other natural disaster (FEMA 2019). It can therefore be argued that the most important application of satellite imagery is flood analysis. Understanding where floods have occurred and where they may occur again can save lives as well as property.

The main objectives in mapping floods are to detect where damage has occurred, how much damage has occurred, and to predict where it may happen again. There are two main mapping strategies to understand where flooding will occur in the future. The most common method involves GIS modeling, primarily based on a DEM (Digital Elevation Model) among other data layers. This method relies on the knowledge of the architect of the model to understand the factors that contribute to where flood waters may appear on the landscape. Also it relies on the accuracy of the independent variable layers that are referenced in the knowledge-based ruleset. Although it is impossible to account for all variables that lead to flooding, and the data layers are never 100% correct, an area of the landscape can be delineated as having higher probability of flooding. There are many of these models, they have been used for decades, and they are well documented. This is not the focus of this paper.

Another method to understand where flooding will occur, is to map where it has occurred in the past. The theory of this approach is that where flooding has been observed before, it is more likely to occur again. Since the analysis is based only on where flood has been observed, it is not necessary to know the factors or rely on various independent variables that may contribute to flooding. In this approach, satellite imagery is collected over the course of decades for a target AOI (Area Of Interest). This can be called a Mult-temporal Satellite Image-based Flood Analysis (MSIFA). Water is automatically extracted from each of the images. Then the water masks from all dates are stacked up and the number of times water has been observed in the masks for each pixel over time is calculated. Then the ratio of number of water observations to number of total observations (how many images with data cover the pixel) is calculated. If there have been no observations of water over the past couple of decades, then it is unlikely that flooding has occurred at that location. If 100% of the pixels are observed as water, then it is likely a persistent water feature such as a lake or river. But between 0 and 100%, water is observed intermittently, which can mean flooding. Some accommodation must be made for errors in the water mask process, so perhaps 80% of calls and above are identified as persistent water features and perhaps 1% and below are identified as persistently dry. But values in between are likely to be flood events. This approach can even distinguish single flood events versus multiple flood events and even seasonal flood events based on how often and at what interval water is observed.

Some flood events occur regularly and are expected. Examples of this are tides and periodic flooding of undammed rivers or streams. These are generally benign events and are of less concern for disaster relief specialists. But flood events that occur after rain or storm events or accidental destruction of a dam are important to document and respond to, and to understand the extent to which flooding may occur the next time it

happens.

The main benefit to this approach is that results of the analysis are based on actual events, not modeled data. This process does not rely at all on the knowledge of the researcher on factors or processes that can cause floods. But there are drawbacks to this approach as well. If using Multi-Spectral (MS) imagery, then it is not a guarantee that the timing of the flood event will be captured by the sensor. For most of the past few decades mid-resolution repeat coverage has been on the order of a couple of weeks. And even if you acquire an image of a flood event within a few days of its peak, it is often full of clouds. So clouds and poor repeat coverage are the biggest disadvantages to an MS satellite image based approach. But SAR imagery can be used to mitigate those issues. Also, flooding patterns can change over time due to human development and climate change. Examples of this are dam construction, large deforestation events, and the construction of impervious surfaces by humans. The results of an MSIFA approach based on MS imagery will always be an underestimation of the peak flood extent.

There are two types of satellite imagery that can be used in a MSIFA: MS imagery and Synthetic Aperture RADAR (SAR) imagery. Each has their benefits and drawbacks. The main benefit of the SAR imagery is better coverage due to the fact the sensor is not nearly as affected by atmospheric conditions or clouds as MS sensors are. The main drawback is water masks can be more noisy and less precise than MS-based masks. Another advantage MS imagery has is a deeper archive of imagery. Landsat imagery dates back 50 years! The products outlined in this document are based on Landsat imagery collected over the past 30 years. According to Orangzeb (2017), Landsat-based flood mapping is more accurate than SAR based.

The Landsat program began in 1972 with the launch of ERTS-1, later named Landsat 1. Landsat 9 was launched September 27, 2021 and there are plans for Landsat 10 as well. Since 1985, when Landsat 5 was launched, an archive of 30m resolution, 6-band+ imagery has been collected around the globe. Currently both Landsats 8 and 9 are continuously collecting all imagery over the earth between 80°N and S. Landsat is particularly suitable for mapping floods because:

- The band wavelengths cover 2 SWIR bands, NIR, and visible spectra
- Radiometric and atmospheric correction processes are very reliable so the imagery can be consistently and accurately transformed to ground surface reflectance
- Resolution is 30x30m
- The imagery is free for public use and available for download from USGS and several cloud computing platforms
- It has the deepest archive of any other EO satellite program, 35 years at 30m resolution
- The program is still being supported by the USG, plans for Landsat 10 are in progress as of the date of this document

- USGS produces and distributes Surface Reflectance, NDVI and NDWI derived from the images for each date, so less work for the analyst
- Scientists have been contributing to research toward Landsat image applications for decades, so algorithms, such as automated water extraction, are well vetted and shared
- The Landsat image archive has been augmented by "harmonized" Sentinel-2 imagery, whereby S-2 images have been transformed to Landsat specifications (Wulder, et al 2021)

There are many examples of mid-resolution multispectral satellite remote sensing approaches for flood extent mapping in the peer-reviewed literature. Here are just a few recent examples.

In a 2015 article, Tamta and Bhadauria discussed an approach to mapping floods whereby they used an Object Based Image Analysis approach. Two Landsat images were acquired, one before a flood event, and one after a flood event. The images were segmented using eCognition and classified for water and then compared in a post-classification change detection. The water classification was based mainly on the Normalized Difference Vegetation Index (NDVI) and This is a simple but effective approach to flood mapping. One drawback is that you have to know when the flood even occurred and have access to clear imagery before and during flooding. This is not as much a problem with approaches that use hundreds of water masked layers.

In a 2021 study, Mehmood et al used a temporal stack, or "data cube", comprised and Landsat 5,7, and 8 imagery. They applied the Modified Normalized Difference Water Index (MNDWI) to percentile images derived from the Landsat stack, and used elevation and land cover data as well. Applying the MNDWI to the lower percentile produced temporary water bodies, while applied to higher percentile images produced more permanent water bodies. They validated the results by determining if the output layer correctly identified flood events in different parts of the world, mainly S and SE Asia and Australia. The results were in the 80% range. One drawback to this approach is that although there is a stack of Landsat imagery, there is no temporal record of the flood. For that, one would need to identify water extent in each date of imagery independently, which is how the OFE is produced.

Also in 2021, Du et al published an article describing their approach to flood extent mapping. It involved leveraging both SMAP and Landsat imagery. SMAP L-band brightness temperatures were used to map a flood event in SE Asia, cyclone Idai. SMAP was used to produce fractional water cover and that along with Landsat water masks were used to train a machine learning classifier (CART) to produce 30m results showing flood extent. The results were compared to SAR-based analysis and were highly correlated. Accuracy was reported as R = 0.87. This approach could be useful for mapping the extent of a single known event.

Qi et al in a 2009 publication used a series of 13 orthorectified Landsat images to map water levels in Poyang lake, China. Water frequency was created from the series, which was then compared to hydrological station data to confirm water level and

elevation. This was used to interpolate a flood isoline which was then compared to a model using 90m SRTM. The Landsat derived flood extent was determined to be much more accurate than the modeled layer. This is an interesting use of the flood frequency layer to determine not only extent, but also the actual elevation at peak flood waters.

Finally, in 2016, members of Geoscience Australia (Mueller et al) employed 27 years of Landsat imagery across Australia to understand the extent of flooding in that country. They developed a water detection algorithm based on a decision tree classifier and a comparison methodology using a logistic regression. The resulting analysis made it possible to distinguish persistent water such as reservoirs, lakes, and rivers from intermittent water from floods. The products from this study were used to study wetlands, aquatic species behavior, hydrologic models, and groundwater recharge. This is a good example of using decades of Landsat imagery to characterize flooding over time over an entire continent.

1.1 OFE Project History

As part of the Flood Apex program, in 2016, Maxar (Formerly MDA Information Systems) engaged in a research endeavor with DHS to produce a sample Observed Flood Extent dataset of historical flood extents for 8 target cities. This project demonstrated the use of historical satellite imagery in mapping previously undocumented flood extents. In 2018, Maxar demonstrated and validated the capabilities of the Observed Flood Extent dataset with DHS Science & Technology under the “New Urban Flood Risk” study. The 8 cities selected were evaluated for the economic impact of having OFE data. This led to full production of the Observed Flood Extent product for FEMA over the Conterminous United States (CONUS), finishing production and updates in early 2020.

2. Historically Observed Flood Extent Products

Maxar partnered with DHS S&T to create a series of products based on a process called Observed Flood Extent (OFE) to determine, based on Landsat satellite imagery, where flooding has occurred in the past 35 years. These data sets are available to the public in tiff format and are projected to UTM WGS84 datum. They are raster layers at 30m resolution. The layer extents are determined by the Landsat path/row grid.

Landsat satellite imagery, Tier 1 and <20% cloud cover, was selected, ordered, processed, and downloaded from the United States Geological Survey. All satellite imagery was processed for surface reflectance and cloud masked. Satellite imagery for the Phoenix, AZ AOI was processed for terrain normalization to flatten high slopes and minimize slope shadow. The National Urban Change Indicator (NUCI) dataset was processed and produced for updates through 2016 for use as a primary dataset in the workflow. Additional ancillary data was collected for the workflow including Digital Elevation Models (DEMs), the National Land Cover Database (NLCD), and OpenStreetMap (OSM) shapefiles. The following datasets were created as part of the OFE series of products:

1. Observed Flood Extent (OFE)

2. New Construction at Risk of Flooding (NCRF)
3. Flood Post New Construction (FPNC)
4. Dates of Detection (DoD)

2.1 Observed Flood Extent (OFE)

After all imagery and datasets were preprocessed, each scene was analyzed with a water detection algorithm that used a combination of 12 spectral indices. The algorithm was based on a confidence level where 4 or more spectral indices had to agree for a single pixel to be considered high confidence water. The algorithm also factored in removing high slopes (using DEMs) and a 1986 urban mask where slopes greater than 5% and urban before 1986 were removed from the watermask. This was to eliminate potential false observations on dark slopes and any water observations of water near urban developments before the year 1986.

After all watermasks were created, they were individually viewed for quality control to manually eliminate corrupt and poorly processed scenes.

Remaining watermasks were documented in a "good list", layerstacked, and statistically analyzed for frequency of occurrence, creating a preliminary Observed Flood Extent layer.



Fig 1. *Observed Flood Extent. Magenta represents the most number of times water has been observed in a pixel and red is the least number of times water has been observed at a pixel.*

2.2 New Construction at Risk of Flooding (NCRF)

Urban masks were created using NLCD as a base with yearly NUCI data to subtract or add changes in urban land cover. Urban masks were created from 1986 to 2016. The layerstack of the watermasks, created during the OFE process, was analyzed with the yearly urban masks to highlight water detections before urban development. For example, if a pixel was identified as new construction in 2006 and the algorithms detected water on that pixel *before* 2006, the pixel was marked as New Construction at Risk of Flooding, indicating the pixel had a history of flooding before it was urbanized.

2.3 Flood Post New Construction (FPNC)

Similar to the NCRF process, the watermask layerstack is analyzed for water observations on a pixel for years *after* the pixel was urbanized, using the yearly urban masks. This pixel was marked as Flood Post New Construction, denoting that water was observed on the pixel after new construction had occurred.



Fig. 2: *Furthermore, open-source research was conducted to gather publicly available flood extents from significant flood events. FEMA also provided National Flood Insurance Program (NFIP) flood insurance claims by Census Block Group. When available, these additional datasets were included as an integral part of the FPNC process for use as validation.*

2.4 Dates of Detection (DoD)

The preliminary OFE layer was further processed with the layerstacks to create a layer that provided information on the dates a pixel was determined to be high confidence water. This was done only for OFE pixels that ranged from 1-3% in water frequency. Each watermask was converted to point shapefiles where each pixel was represented by a point. Each point was assigned the date of its associated Landsat satellite image. A querying python script determined the oldest date, most recent date, and 3 additional random dates that the pixel was determined to be water from the full temporal range of the satellite imagery. The outcome produced Dates of Detection, a vector geodatabase of points per pixel that provided temporal information on when that pixel was detected as water.



Fig. 3: *Date of Detection. A point exists at each 30m pixel within 1 - 3% water frequency in the OFE layer, and each point is attributed by the date or dates water was detected at that pixel. These are likely the areas of flood events.*

As part of final quality control, the preliminary OFE layer went through a manual QC process to eliminate potential false water observations. The DoD geodatabase was used to identify the date a pixel was called water, observe the imagery from that date and verify the pixel was water. If it was determined to not be water in the satellite image, it was removed from OFE. After the final quality control was completed, anything removed from OFE was subsequently removed from NCRF, FPNC, and DoD.

A stratified random point sample validation test was conducted on OFE. There was an average of 300 satellite images available for each AOI, with 800 images available for the Phoenix, AZ AOI. Because of this, it is statistically significant that water could be observed on a pixel *at least once* in higher frequencies. Validation points were generated for only the 1-3% range of OFE. 30 total points per AOI were generated, 15 in 1-3% water occurrence zones and 15 in areas where water was never detected. A quality control analyst used the DoD geodatabase to observe all dates associated with each validation point. A score of '0' was given if it was incorrectly detected as water or if it was incorrectly detected as being not water. A score of '1' was given if it was correctly detected as water or if it was correctly detected as land. The final score was based on an average of correct calls from the total number of images that were viewed during the QC process.

The products are offered in a fixed, non-overlapping tiled system in Albers projection. The tiles are aligned with the USGS ARD tile system. Each tile covers 5000 x 5000 30-meter pixels (22,500 km^2 area) and the sides are 150km in length (Dwyer et al 2018).

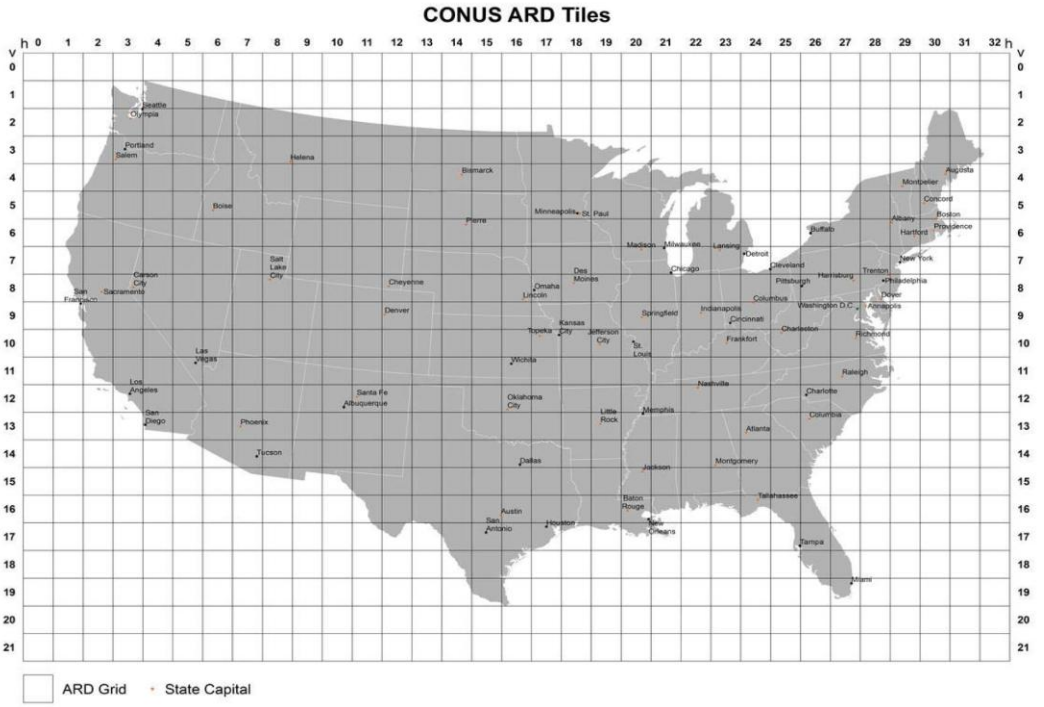


Fig. 4: *The Landsat ARD tile system for the conterminous US from USGS.*

The tiles for each product are named by the following conventions:

- Water count: [tile]_[state]_ofe_watercount.tif
- NCRF: [tile]_[state]_ofe_ncrf.tif
- Dates of Detection: [tile]_[state]_ofe_dod.gdb and [tile]_[state]_ofe_dates

3. Application of OFE Products

One study by Smith and Alexander showed how OFE data can be used to understand how flooding impacts land cover change (Smith and Alexander 2018). In this study it was asked: does a flood tend to change how the land is used or what features cover it? Also, is there a relationship to how many times land is flooded to what the land cover is changed to? To try to answer these questions, the authors took the OFE water frequency data near Shreveport Louisiana and 4 dates of NLCD (National Land Cover Dataset) from USGS and calculated bivariate (from-to) land cover change between the 4 dates of land cover. Then those bivariate change layers were intersected with the OFE data so that amount of from-to class change can be known for each frequency of observed water.

It was discovered that land cover changes in this study area more often occurred within areas that had flooded, rather than areas that had not flooded. Barren land cover change was clearly associated with flooding. Agricultural land changing to barren suggested that frequent flooding may cause arable land to not be as productive. When Barren land changes to vegetated cover and when Water changes to Barren, there is a strong likelihood that the change was due to flooding. Interestingly, Urban land cover changes intersected with flood frequency regardless of the ratio. Over 2600 ha of Urban were built within the areas that had previously flooded.

The results of this analysis are very useful for identifying where land cover change areas exist, their extent, and the likelihood they are associated with flood activity. This has implications and applications to floodplain management and community land use planning. The results of this study showed there is a relationship between some land cover change types and areas that frequently flood.

3.1 How to Use OFE Products

To use the OFE datasets yourself, download them from the DHS website:

- https://fema-ofe-3124468.appspot.com/
- Register an account with your email and log in
- Select your tiles and right click when you are ready to download
- Dark Green tiles mean data is available, Light Green tiles means it has recently been updated within the last 7 days, Red cells have yet to be processed
- Information about the data is available in the drop down menu.

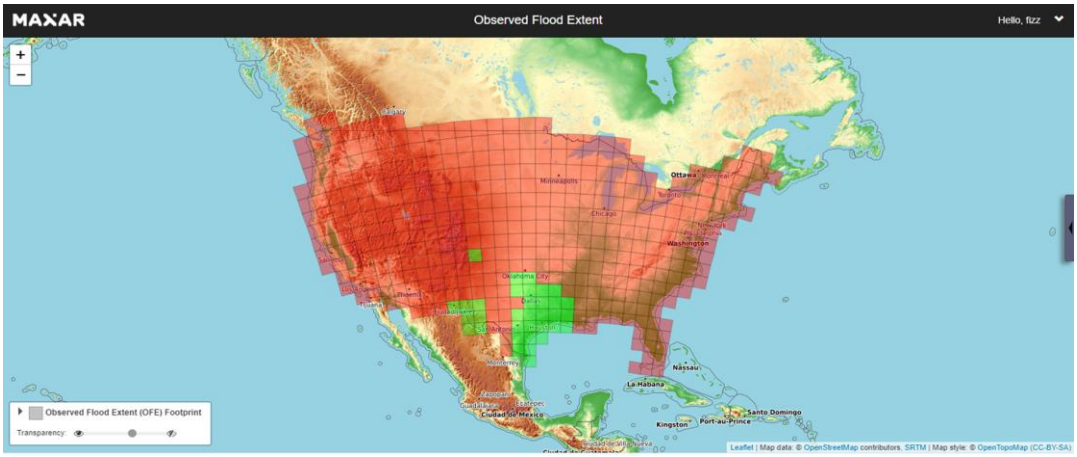


Fig. 5: *OFE User Interface.*

The download package includes:

- [tile]_[state]_ofe_dod.gdb
- [tile]_[state]_ofe_ncrf.tif
    - Ncrf_color_scheme.lyr
- [tile]_[state]_ofe_watercount.tif
    - Water_count_color_scheme.lyr
- [tile]_[state]_ofe_metadata.txt

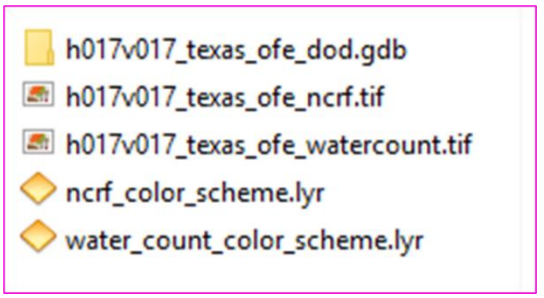


Fig. 6: *OFE Download Package.*

The raster datasets are in tiff format, Albers projection, WGS84 datum and spheroid, and 30m resolution. The vector datasets are ESRI's geodatabase format with the same projection attributes. The format images can be viewed and analyzed in many different

platforms including ArcGIS, Hexagon's ERDAS Imagine, ENVI, and the open-source package QGIS. The ESRI geodatabase requires ArcGIS or other ESRI products for viewing and manipulation.

Once the data has been downloaded it can viewed in a number of popular image processing or GIS packages such as ESRI's ArcGIS, Hexagon's ERDAS Imagine, L3 Harris' ENVI, or open source packages such as QGIS. In Figure 6 below, a tile has been downloaded, h017v017, which covers the town of Katy Texas. Figure 6 shows the Water Count layer at the full tile scale.

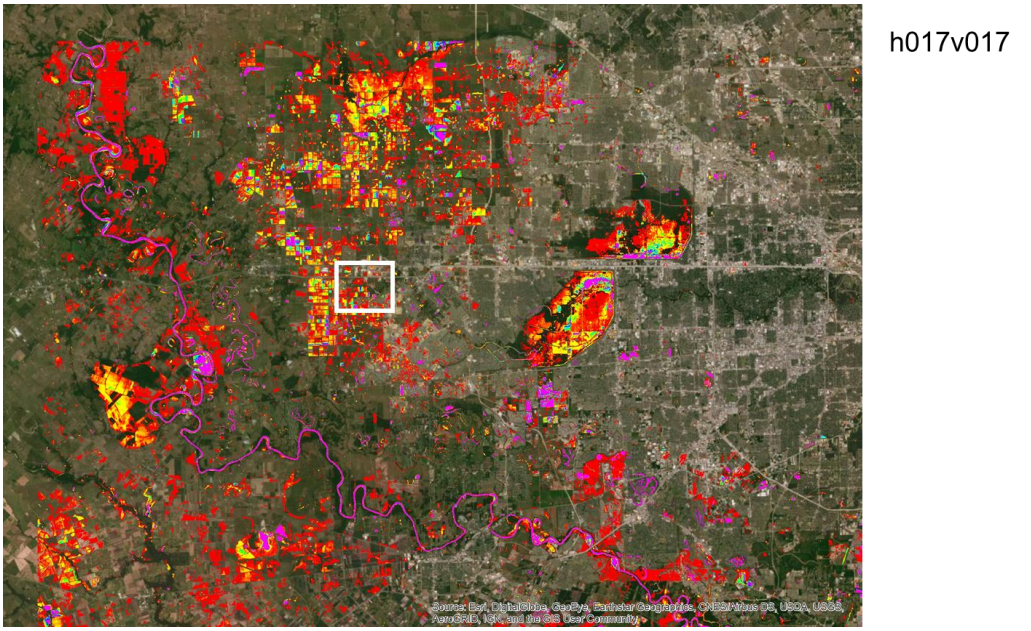


Fig. 6: *An OFE Water Count example in Katy, Texas.*

Figure 7 shows a zoomed area corresponding to the white box in Figure 6. The color scale goes from low values which are red to high values which are magenta. The layer represents how many times in a stack of Landsat images a pixel has been identified as water. The red pixels have only been identified as water a few or even one time. The magenta pixels have been identified more than 50 times. Generally there are up to a couple hundred or so scenes in the temporal stack. This means the magenta pixels are likely "permanent" water features such as rivers, streams, lakes, ponds, or reservoirs. That term is in quotes because as we know, no features are truly permanent as the Earth's landscape is constantly changing. Red pixels are likely areas of flooding and are of great interest for many applications. The colors in between: yellow to green to blue, signify areas that are intermittently flooded. That often includes features such as water retention ponds, drainage ditches, wetlands, areas you would expect to fill with water after rainfall events. With this information, you can begin to understand which areas

have been damaged by flooding events, and perhaps which areas will be more prone to flooding in the future. You can distinguish between areas where you would expect to find surface water, where you would expect it to accumulate after a rain event, and where if it is observed, flooding has occurred. This is important information for city planners, insurance adjusters, developers, homeowners, farmers, and hydrologists.

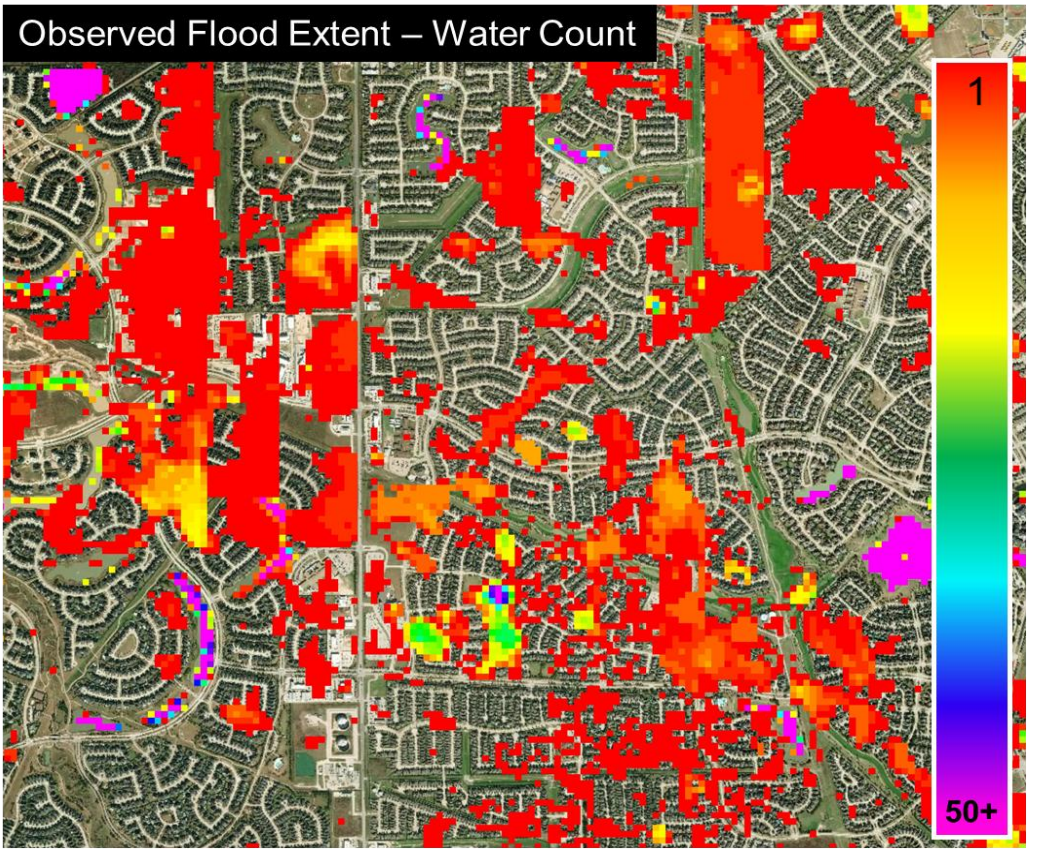


Fig. 7: Zoom in of Fig. 6, Water Count for Katy Texas.

Figure 8 shows a different OFE layer, New Construction at Risk of Flooding (NCRF). This layer shows urban areas impacted during inundation events at specific years. The areas in blue were last inundated as far back as 1988, while areas in red were last inundated more recently, as late as 2019 in this example. Green and yellow pixels were last observed as flooded in the early 2000's. This data is important for understanding the distribution of the impact of floods on urban structures over time and space. This information is important for many industries including real estate and development.

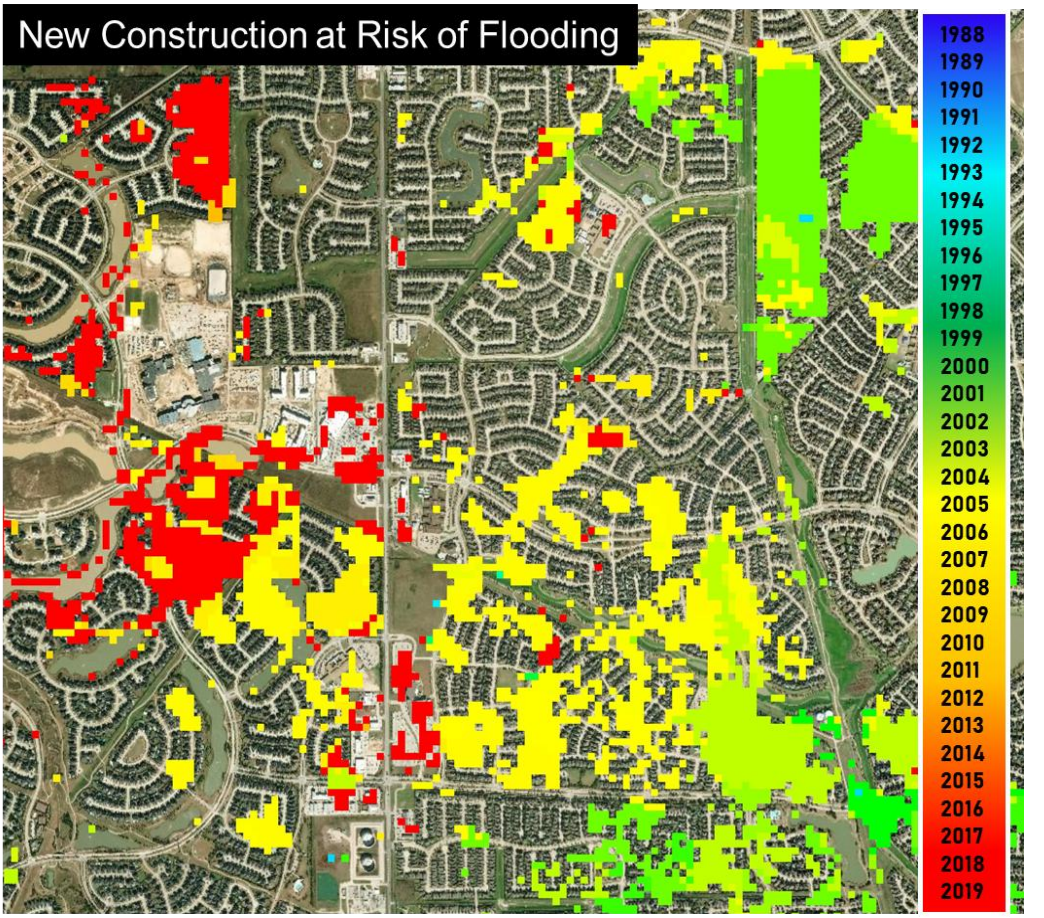


Fig. 8: OFE layer, New Construction at Risk of Flooding.

The OFE layer in Figure 9 is simple, the Dates of Detection of water inundation. It is a point feature layer in Arc's geodatabase format. It allows the user to click on a point to display the date of when inundation was observed at that point. It is a different format for similar information in the NCRF layer.

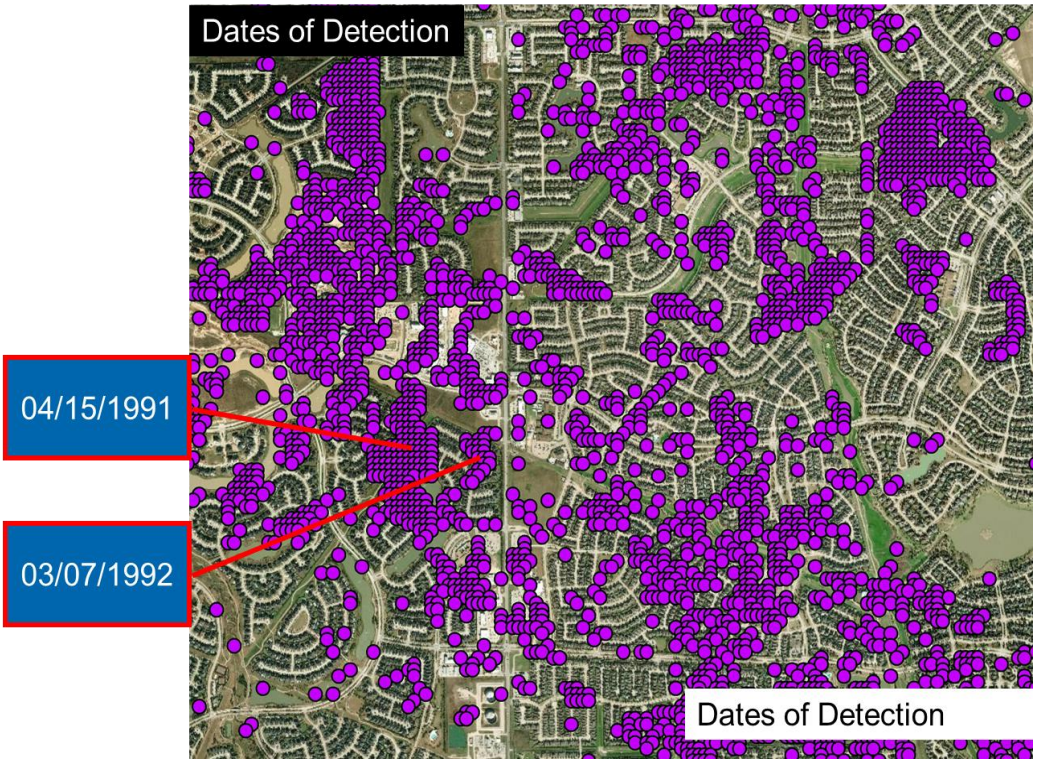


Fig. 9: OFE layer, Dates of Detection.

Figure 10 shows this same general area in Texas where there were inundated pixels in 1991 and 1992, and by 2010, new construction of homes began in the same area. By 2016, the entire area was covered by development. This is important to understand because even if there were flood mitigation measures implemented during the development, the water that was accumulating there and that would continue to accumulate there must go somewhere. That means there is more pressure on the hydrological system further downstream from this area, which increases the possibility of flooding elsewhere. Furthermore, if flooding occurs in this same location post-development, it could mean that flood mitigation measures failed.

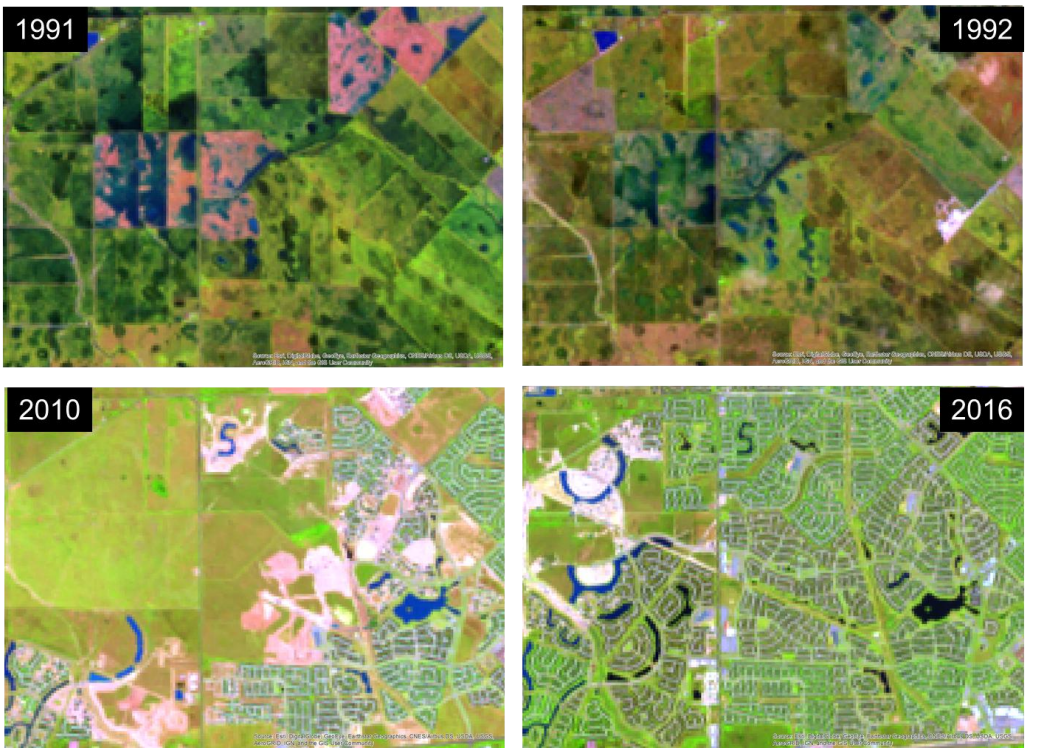


Fig. 10: Four snapshots in time in a small area in Texas showing residential development on previously flooded land.

4. Summary

The OFE product shows that it is plausible to use Landsat imagery collected over many dates to build layers to estimate where and on what day flood events have occurred over the past 30 years. The OFE datasets characterize where and when observed flood events have occurred over the past 30 years. They also show where new buildings have been erected over areas where water inundation has occurred prior to construction. Not all flooding that has occurred in the target areas will be captured. It depends on the availability of Landsat imagery and is limited by cloud cover. These datasets can be used for many applications that require understanding the extent and timing of water inundation over the landscape.

Any user in the US can register with the DHS website, download OFE datasets, and analyze the data for themselves.

5. Key Themes, Questions, and Additional Readings

5.1 Key themes

Key themes that emerged from the development of the historically observed flood extents products using remote sensing were:

- Co-creating with end-users is a necessity to ensure the product is both scientifically sound and usable
- Providing example use cases on how to use the product was critical.
- Having a multi-decadal view of historical flood extents was useful toward understanding how flood risk is changing over time and how it may differ under future climate extremes and changing conditions.
- Empowering local community agencies to be able to evaluate flooding, impacts and risk must be intuitive and delivered in a GIS-ready format.

5.2 Discussion questions

- How does remotely sensed flood data analysis differ from flood analytic modeling?
- What are the limitations of using remotely sensed data for flood analysis, particularly in respect to flood extents?
- What criteria should be considered when developing a flood analysis and extent products?
- What techniques could be used to address the spatio-temporal analysis and visualization of historical flood data?
- What kind of information would you want to share with the public? What message would you want to convey?
- This publication presented use cases for using historical flood extent data, including case studies in the Charleston, SC and Shreveport, Louisiana areas. What other flood studies could be conducted? Are there uses cases for the area where you live?

5.3 Additional Readings

- MAXAR Blog on detecting urban change over time – https://blog.maxar.com/earth-intelligence/2018/detecting-30-year-urban-change-using-persistent-change-monitoring
- FEMA Historical Flood Risks and Costs Interactive Data Tool – https://www.fema.gov/data-visualization/historical-flood-risk-and-costs
- Framing the Challenge of Urban Flooding in the United States – https://www.ncbi.nlm.nih.gov/books/n/nap25381/pdf/

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Assessing Disaster Resilience in North Carolina: An Empirical Study of Hazard Mitigation Projects Undertaken Following Hurricane Floyd and the Consequences of these Actions After Hurricane Matthew

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Abstract

The purpose of this study was to improve the understanding of the impacts of state and local level mitigation actions intended to enhance community resiliency, support effective and equitable recovery, and reduce flood fatalities and losses by providing an empirical analysis of the post-Hurricane Floyd (1999) statewide mitigation actions and the consequences of Hurricane Matthew (2016). The study examined the impacts of Hurricane Matthew flood hazard mitigation actions implemented in each of six study counties in North Carolina after Hurricane Floyd in 1999. The study builds on theory developed by the scientific community about community resilience. Part one of the study explored whether 17 theoretical indicators of resilience demonstrated if communities saved time and money during the recovery process for Hurricane Matthew. Part two of the study examined losses avoided to determine whether the acquisition of flood-prone properties by county and municipal governments increased resilience following Hurricane Matthew. Hazard mitigation projects analyzed in the study were implemented after Hurricane Floyd, which struck the coast of North Carolina in 1999 and caused $2 billion in damage, and before Hurricane Matthew, which caused $967 million in North Carolina. This study helped improve the understanding of how indicators of resilience and flood hazard mitigation efforts relate to the experience of communities damaged from hurricanes. In this case through a case study of Hurricanes Floyd and Mathew in North Carolina.

Keywords

Disaster recovery, mitigation, risk indicator

1. Introduction

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"There is now a widely held recognition among diverse sectors of the nation that a lasting economical, and sustainable solution to the flood problem preventing future catastrophes of the magnitude of 1993 can and must be achieved through integrated action." (White 1994)[40]

This chapter describes the results of an empirical study conducted to assess the impacts of state and local hazard mitigation actions undertaken following Hurricane Floyd (1999) on the subsequent consequences experienced by communities following Hurricane Matthew (2016). The study was conducted as part of a larger research portfolio of projects overseen and supported by the Department of Homeland Security, Office of Science and Technology's Flood Apex Program, which was created in 2014. The key objectives of the Flood Apex Program are to reduce fatalities and property losses from future flood events; increase community resilience to disruptions caused by flooding; and develop better investment strategies to prepare for, respond to, recover from, and mitigate against the effects of flood hazards.

This study applied empirical measures of pre-Hurricane Matthew conditions (indicators of resilience) and Hurricane Matthew outcomes in six eastern North Carolina counties. This study initially analyzed 88 paired comparisons of measures of resilience and measures of Hurricane Matthew outcomes. Seventeen indicators of resilience (independent variables) were ultimately selected and compared to post-Hurricane Matthew outcomes (dependent variables). We hypothesized that higher indicators of resilience would lead to less damage sustained by privately owned structures and public infrastructure and that the time required to recover would be reduced.

A paired comparison approach was selected because the small sample size (six counties) was insufficient to use simple linear regression. The findings of the study suggest that, as hypothesized:

- A lower percentage of low- to moderate-income households makes a community more resilient.
- A higher percentage of homeownership makes a community more resilient.
- A lower percentage of mobile homes makes a community more resilient.
- A larger number of road and bridge projects completed after Hurricane Floyd (measured as completed with FEMA Public Assistance funding) made communities more resilient than communities with fewer projects completed.

2. Literature Review

Resilience is "the ability to face internal or external crisis and not only effectively resolve it but also learn from it, be strengthened by it and emerge transformed by it,

[40] Gilbert White (1994). Personal correspondence with Gerald Galloway, Chair, Federal Interagency Floodplain Management Review Committee.

both individually and as a group" (Brenson-Lazan, 2003). A review of resilience theory identified approximately 100 indicators of community resilience spanning physical characteristics, disaster management experience, administrative capability, as well as economic and social conditions. To reduce the number of resilience indicators used in the study, those that could not be measured empirically, or data was not available at the county level were removed from consideration. Seventeen indicators of resilience were ultimately selected and categorized across social, economic, physical environmental, and disaster management capacity themes.

Social resilience has been defined as "the capacity of a social entity (e.g., a group or community) to 'bounce back' or respond positively to adversity" (Maguire and Hagan, 2007). Measures of social resilience include a community's absorptive, adaptive, and transformative capacities. Absorptive capacity pertains to a community's ability to persist in the face of a disaster. Adaptive capacity is the community's ability to adjust incrementally to the impacts associated with disasters over time. Transformative capacity is reflected in a community's ability to create a new system or framework to respond to future disasters (UNDP, 2014). The four key components of social resilience (Sapirstein, 2006) include the following characteristics:

- Actions taken in response to an event.
- Community self-organization.
- Learn from past disasters.
- Developing new policies and strategies to prepare future events.

The components of social resilience can be enhanced by strong social networks of non-governmental groups or organizations that support their members and others in the community. This type of support provides for the basic needs and services of those affected by disasters, which helps individuals and communities return to normalcy more quickly following extreme events than if it they did not have this support and to take actions that reduce future vulnerability. Some researchers suggest that the social components of vulnerability and resiliency are difficult to measure because social vulnerability focuses on demographic characteristics of individuals within a community but does not necessarily include the "social factors that influence or shape the susceptibility of various groups to harm and that also govern their ability to respond" (Cutter et al., 2003). Therefore, other measures should be included to understand the social characteristics of communities that have socially vulnerable populations. In order to address this issue, this study combines two categories to measure social resiliency: social vulnerability and social capital. Berke et al., (2015) describes social vulnerability as being comprised of the following characteristics: socioeconomic status, household composition, minority status, and housing/transportation. The Centers for Disease Control and Prevention (CDC) uses a similar set of variables in its social vulnerability index. The CDC defines social vulnerability as "the degree to which a community exhibits certain social conditions, including poverty, car ownership, or number of persons in households, [that] may affect that community's ability to prevent human suffering and financial loss in the

event of a disaster" (CDC, 2015). All three examples recognize that socially vulnerable populations are at greater physical and economic risk during a disaster and require more assistance to recover afterwards.

Economic resilience is defined by Rose (2004) as the ability or capacity of a system to absorb or take actions that limit damage or loss. It is further defined by Rose (n.d.) to be both static and dynamic. Static economic resilience is characterized by the efficient use of the resources available at a given point in time, while dynamic economic resilience involves the efficient use of resources over time to include investments in repair and reconstruction. Together, the two elements of economic resilience capture the economy's ability to continue functioning and respond to a shock. Achieving enhanced levels of economic resilience requires the adoption of effective strategies that can better prepare communities or regions for natural or manmade events that impact the economy. Activities may include maintaining adequate flood insurance coverage, adhering to building codes and standards, maintaining adequate financial savings, and developing emergency protocols for data and inventory.

Another way to define resilience is the ability "to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions" (NIST, 2016). This definition helps to unpack the characteristics of *physical resilience*, to include the ability of buildings and infrastructure to remain functional or quickly become functional after a disaster due to the adoption of preparation protocols, the adoption of hazard mitigation and adaptation measures, and the development of disaster recovery policies and investments that foster a more efficient recovery following disasters. It is important for communities to achieve as high a level of physical resilience as economically feasible because it is essential that buildings and infrastructure remain operational for modern societies to thrive and endure over time. Buildings and infrastructure provide shelter, access to public services (power, water, sewer), and support business continuity and the larger economy. Physical resilience is achieved through the adoption of disaster resilient construction practices, building codes and standards that reflect local conditions, sound floodplain management, land use planning best practices, wise capital investments, and other applicable regulations (Twigg, 2009). The natural environment (topographical features, local ecosystems, and water resources) is also an important component of physical resilience. The interaction between the physical and natural environments help to define community resilience, which can be expressed through recovery times and return of functionality (NIST, 2016).

Risk and disaster management resilience is part of the broader concept of resilience; it is defined as "the ability of individuals, communities, public and private organizations, and all levels of governments to minimize the impacts and recover from disaster events, while positively adapting to long-term changes and uncertainty" (OECD, 2013). Similarly, the Hyogo Framework for Action suggests that resilience is focused on the capability of communities to organize themselves to learn from past disasters and to reduce their risks to future events (UNISDR, 2005).

"Risk and Disaster Resilience" is one of the seven core capabilities identified in

FEMA's National Mitigation Framework (US DHS, 2016). Assessing risk and disaster resilience involves evaluating potential threats, hazards, vulnerabilities, consequences, needs, and resources. After defining risk, emergency management officials and decision makers can use this information to prioritize risks and make informed decisions to better prepare for, respond to, and recover from potential disaster events. Risk and disaster management resilience capacity can be increased through three types of actions:

- Political actions: Political actions taken to enhance community or state capabilities to deal with disaster events may include enacting legislative changes, devising new policies, creating funding programs, integrating hazard mitigation into land use or capital improvement planning, and adopting building codes.
- Institutional actions: Institutional actions may include developing disaster response and recovery plans, completing Threat and Hazard Identification and Risk Assessments (THIRA), and expanding emergency management capacity.
- Technical actions: Technical actions may include utilizing tools such as digital flood mapping, Web-Based Emergency Operations Center (WebEOC), LiDAR, and initiating online public outreach and risk information dissemination programs.

3. Research Methods

This study identified and applied resilience indicators to measure the effects of hazard mitigation actions undertaken in six North Carolina counties. The six hurricane-prone counties selected for the study include Bertie, Columbus, Edgecombe, Lenoir, Robeson, and Wayne.

A review of resilience theory identified approximately 100 different indicators of resilience. The indicators help to understand the characteristics of a community, including its physical environment, disaster management experience, local government capability, and economic and social conditions. Indicators that could not be measured empirically or did not pertain to a county were removed from consideration. For example, building code and freeboard regulations were removed because the State of North Carolina has a building code that is applied statewide, so there is no variation across the six counties. In addition, all six study counties require structures in Special Flood Hazard Areas to be elevated at least 2 feet above the NFIP-designated base flood elevation. The total number of resilience indicators used in this study was reduced to 17 (Table 1).

Table 1: Selected Indicators of Resilience and Supporting Literature

Indicator of Resilience	Supporting Literature
Individual wealth	

Indicator of Resilience	Supporting Literature
Percent of low to moderate income households	Morrow (2008); Norris et al. (2008); Cutter et al. (2010); Peacock (2010); BRR (2011); Mit-FLG (2018)
Per capita income	
Median monthly household income Individual wealth	
Homeownership rate	Prevention Institute (2004); Morrow (2008); Wagner et al. (2008); Norris et al. (2008); Cutter et al. (2010); Peacock (2010); BRR (2011); Cutter et al. (2014)
Health of population	
Healthcare availability	Mit-FLG (2016), Cutter et al. (2014), Rockefeller Foundation (2014), Cutter et al. (2010), Peacock (2010), Prevention Institute (2004)
Food insecurity	Cutter et al. (2010), Peacock (2010)
Availability of parks	Burby et al. (2000); Cutter et al. (2010), Peacock (2010), Prevention Institute (2004)
Unemployment	Flanagan et al. (2011); Cutter et al. (2014); Mit-FLG (2016)
Educational attainment	Cutter et al. (2010); Peacock (2010)
Access to a vehicle	Prevention Institute (2004); Cutter et al. (2010); Peacock (2010); Tierney (2009); Flanagan et al. (2011); Cutter et al. (2014); Berke et al. (2015)
Housing stock type	Berke et al. (2015); Cutter et al. (2014); Flanagan et al. (2011)
Housing constructed before the county joined NFIP	Burby (2001)
Value of owner-occupied housing units	Morrow (2008); Norris et al. (2008); Cutter et al. (2010); Peacock (2010); BRR (2011)
Road and bridge projects completed after Hurricane Floyd (funded by the FEMA PA program)	Berke and Campanella (2006); Cutter et al. (2010); Peacock (2010); Sempier et al. (2010)
FEMA-funded hazard mitigation projects (housing)	Berke and Campanella (2008); Cutter et al. (2010); Peacock (2010); Sempier et al. (2010); Committee on Increasing National Resilience to Hazards and Disasters (2012)
Plan Integration	Flynn (2014); Berke et al. (2015)
Flood insurance coverage	Burby (2001)

Indicator of Resilience	Supporting Literature

NFIP= National Flood Insurance Program

PA = Public Assistance

Once identified, the 17 indicators of resilience were categorized across the following themes: social, economic, and physical environment, and disaster management capacity of a community.

For each theme, independent and dependent variables were identified. Independent variables used in the exploratory examination of resilience are measures of pre-hurricane conditions identified in the literature. The study also examines flood hazard mitigation actions as a potential indicator of resilience. Dependent variables used in the exploratory examination include measures of Hurricane Matthew outcomes. The exploratory examination consisted of paired comparisons of independent variables with dependent variables across the six counties to learn whether indicators of resilience led to less damage and faster recovery.

Eighty-eight paired comparisons were made between measures of resilience indicators and measures of Hurricane Matthew outcomes. Thirty-two comparisons were made relative to the time required for recovery from Hurricane Matthew, and 56 paired comparisons made relative to the costs associated with recovery from Hurricane Matthew. The study did not use simple linear regression because the sample size of the six counties was too small to conduct statistically sound simple linear regression analysis for inferring relationships between an indicator of resilience and a measure of Hurricane Matthew outcomes. However, the paired comparison approach is similar to methods used in simple linear regression studies.

3.1 Social Indicators of Resilience

The following hypotheses regarding social indicators of resilience include:

- A higher rate of low- to moderate-income households makes a community less resilient.
- A higher per capita income level makes a community more resilient.
- A higher median monthly household income makes a community more resilient.
- A higher rate of homeownership makes a community more resilient.
- Greater availability of primary care physicians makes a community more resilient.
- Greater food insecurity makes a community less resilient.
- Greater availability of parks makes a community more resilient.

Indicator data presented in this section are shown in Table 2. Comparative levels of resilience are assessed across the six study counties with a score of 6 indicating the highest level of resilience and 1 the lowest. The summed ranking for each county

reflects its expected social resilience relative to other counties. Based on the sum of social indicators of resilience, Edgecombe County was shown to be the least resilient after Hurricane Matthew.

Table 2: Social Indicators of Resilience Composite Scores

	County (Rank)					
Indicators	**Bertie**	**Columbus**	**Edgecombe**	**Lenoir**	**Robeson**	**Wayne**
Percent of low- to moderate-income households	6	4	2	3	1	5
Per capita income	2	5	3	4	1	6
Median monthly household income	1	4	3	5	2	6
Homeownership rate	6	5	1	3	4	2
Healthcare availability(1)	2	3	6	5	4	1
Food insecurity(2)	2	4	1	4	3	5
Parks(3)	1	4	3	5	6	3
Sum	**20**	**29**	**19**	**29**	**21**	**28**

(1) Primary care physicians per 100,000 population

(2) Percent of food insecure population

(3) Total number

3.2 Economic Indicators of Resilience

The following hypotheses regarding economic indicators of resilience include:

- A higher rate of unemployment makes a community less resilient.
- A higher level of educational attainment makes a community more resilient.
- A higher percentage of residents with access to a vehicle makes a community more resilient.

Data related to economic indicators of resilience are shown in Table 3. Comparative levels of resilience are assessed across the six study counties with a score of 6 indicating the highest level of resilience and 1 the lowest. The summed ranking for each county reflects its expected economic resilience relative to other counties. Based on the sum of economic indicators of resilience, Bertie and Edgecombe Counties were shown to be the least resilient after Hurricane Matthew.

Table 3: Economic Indicators of Resilience Composite Scores

	County (Rank)					
Indicators	**Bertie**	**Columbus**	**Edgecombe**	**Lenoir**	**Robeson**	**Wayne**
Rate of unemployment[1]	5	4	1	2	6	3
Educational attainment[2]	1	5	3	4	2	6
Access to a vehicle[3]	1	6	3	2	4	5
Sum	**7**	**15**	**7**	**8**	**12**	**14**

(1) 3-year average

(2) Percent completing high school or beyond

(3) Percent of households

3.3 Physical Indicators of Resilience

The following hypotheses regarding physical indicators of resilience include:

- A higher percentage of housing stock that is not mobile homes makes a community more resilient.
- A higher number of homes built before a community joined the NFIP makes a community less resilient.
- A higher median value of owner-occupied housing units makes a community more resilient.
- A higher number of road and bridge projects completed after Hurricane Floyd makes a community more resilient.

Indicator data related to physical resilience are shown in Table 4. Comparative levels of resilience are assessed across the six study counties with a score of 6 indicating the highest level of resilience and 1 the lowest. The summed ranking for each county reflects its expected physical resilience relative to other counties. Based on the sum of the economic indicators of resilience of each county in the study, Robeson County was shown to be the least resilient after Hurricane Matthew.

Table 4: Physical Indicators of Resilience Composite Scores

	County (Rank)					
Indicators	**Bertie**	**Columbus**	**Edgecombe**	**Lenoir**	**Robeson**	**Wayne**
Housing stock type [1]	2	3	6	5	1	4
Housing constructed before county joined the NFIP[2]	5	1	4	3	6	2

Indicators	County (Rank)					
	Bertie	Columbus	Edgecombe	Lenoir	Robeson	Wayne
Value of owner-occupied housing units[3]	2	4	3	5	1	6
Road and bridge projects completed after Hurricane Floyd[4]	2	6	5	4	1	3
Sum	**11**	**14**	**18**	**17**	**9**	**15**

[1] Percent not mobile homes;

[2] Percent units

[3] Median

[4] Funded using FEMA PA program grants

3.4 Disaster Management Indicators of Resilience

The following hypotheses regarding disaster management indicators of resilience include:

- A higher rate of completing FEMA-funded housing hazard mitigation projects makes a community more resilient.
- A greater number of planning mechanisms makes a community more resilient.
- A higher rate of flood insurance coverage makes a community more resilient.

Indicator data related to physical indicators of resilience are shown ranked in Table 5. Comparative levels of resilience are assessed across the six study counties with a score of 6 indicating the highest level of resilience and 1 the lowest. The ranking for each county reflects its expected disaster management resilience relative to other counties. Based on the sum of the disaster management indicators of resilience of each county in the study, Columbus County was shown to be the least resilient after Hurricane Matthew.

Table 5: No sequence specified.: Disaster Management Indicators of Resilience Composite Scores

Indicators	County (Rank)					
	Bertie	Columbus	Edgecombe	Lenoir	Robeson	Wayne
FEMA-funded hazard mitigation projects	3	1	5	6	2	4

Indicators	County (Rank)					
	Bertie	Columbus	Edgecombe	Lenoir	Robeson	Wayne
Integration of planning mechanisms [1]	4	1	3	4	2	4
Flood insurance coverage[2]	5	1	6	3	4	2
Sum	**12**	**3**	**14**	**13**	**8**	**10**

[1] Based on the total county-level planning mechanisms

[2] Percent of households with NFIP coverage

3.5 Dependent Variable Measures

This section describes the measures of the dependent variables used in the study and identifies the source of each measure. Raw data were adjusted for differences in the population of each of the study counties using population or total housing unit estimates for 2016 through the U.S. Census Bureau American Fact Finder. The individual dependent variable measures are described below. Table 6 shows a summary of the dependent variable measures.

Table 6: No sequence specified.: Dependent Variables

County	No. Days Schools Were Closed	No. Days DRC Operated	No. Road Closures Due to Matthew	Occupied Housing Units[a] Rec'd NFIP Payments after Matthew	Avg. NFIP Payment	Occupied Housing Units[a] Rec'd Housing Damage Assistance through IHP	Avg. IHP Housing Damage Assistance Payment	Total FEMA PA Program Award after Matthew
Bertie	9	45	26	2.15%	$32,526	8.07%	$1,052	$866,485
Columbus	NA	79	43	0.46%	$40,393	12.70%	$1,628	$2,821,106
Edgecombe	19	122	59	1.49%	$47,664	8.57%	$3,751	$6,619,322
Lenoir	16	60	60	1.13%	$92,852	6.52%	$1,802	$4,767,807
Robeson	23	122	184	0.89%	$50,353	21.07%	$1,750	$26,080,608
Wayne	12	95	161	0.95%	$64,406	6.47%	$2,223	$6,531,370

(a) U.S. Census Bureau, 2016

DRC = Disaster Recovery Center; NA = not available; IHP = Individuals and Households Program; PA = Public Assistance

4. Findings

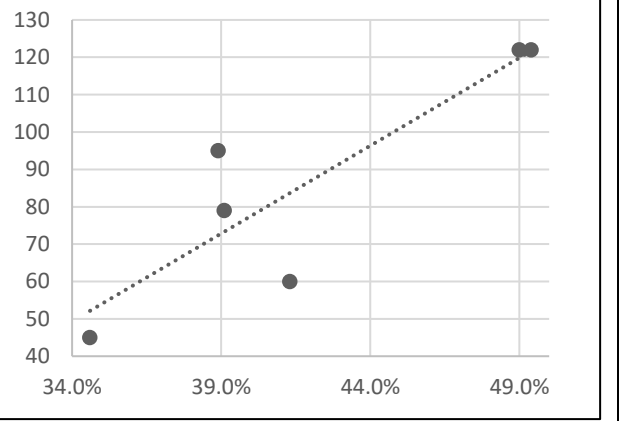
Each hypothesis suggests that higher levels of a given resilience indicator should have led to less damage to privately owned structures or to the public infrastructure and a less time-consuming recovery following Hurricane Matthew. Eighty-eight paired comparisons were made between measures of an indicator of resilience and measures of Hurricane Matthew outcomes. Thirty-two comparisons were made relative to the time required for recovery from Hurricane Matthew, and 56 paired comparisons were made relative to the costs associated with recovery from Hurricane Matthew.

The findings of the paired comparisons of resilience indicators and Hurricane Matthew outcomes are presented next.

4.1 Social Indicators of Resilience

Each of the hypotheses regarding social indicators of resilience presented in the previous discussion was examined relative to measures of the time required for recovery from Hurricane Matthew to occur. Data support the hypothesis that a higher rate of low- to moderate-income households makes a community less resilient. Having a higher rate of low- to moderate-income households seems to be associated with both a slower recovery from a disaster measured as the number of days the DRC was kept open and the number of days until public schools re-opened (Figure 1).

County	Low to moderate income households	Number of days the DRC was open
Bertie	34.6%	45
Wayne	38.9%	95
Columbus	39.1%	79
Lenoir	41.3%	60
Edgecombe	49.0%	122
Robeson	49.4%	122



County	Low to moderate income households	Number of days until all public schools re-opened
Bertie	34.6%	9
Lenoir	41.3%	16
Edgecombe	49.0%	19
Robeson	49.4%	23
Wayne	38.9%	12

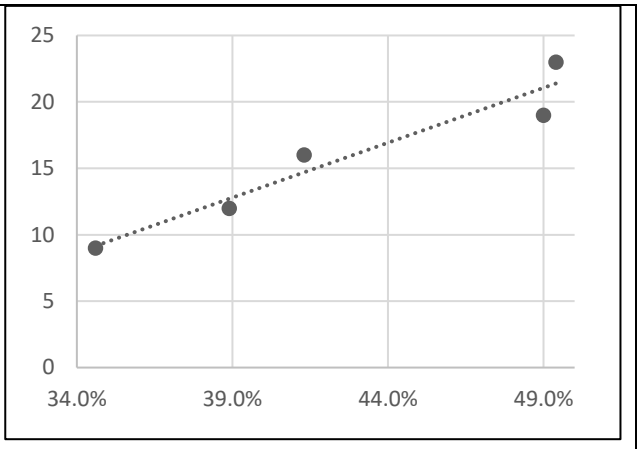
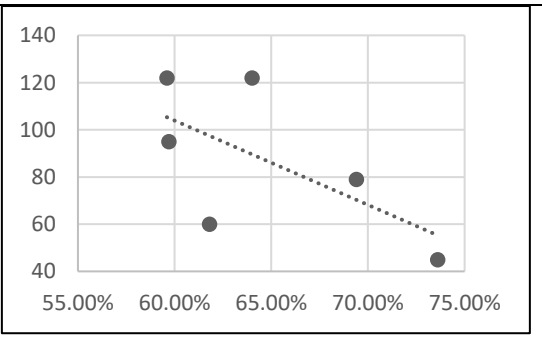


Fig. 1: Paired Comparisons of Percent Low- to Moderate-Income and Recovery Time

Data also support the hypothesis that a higher rate of homeownership makes a community more resilient. Having a higher rate of homeownership seems to be associated with both a quicker recovery from a disaster measured as the number of days the DRC was kept open and the number of days until public schools re-opened (see Figure 2).

County	Percent homeownership	Number of days the DRC was open
Edgecombe	59.60%	122
Wayne	59.70%	95
Lenoir	61.80%	60
Robeson	64.00%	122
Columbus	69.40%	79
Bertie	73.60%	45

Paired comparisons of measures of one indicator of resilience with one Hurricane Matthew outcome



County	Percent homeownership	Number of days
Edgecombe	59.60%	19
Wayne	59.70%	12
Lenoir	61.80%	16
Robeson	64.00%	23
Bertie	73.60%	9

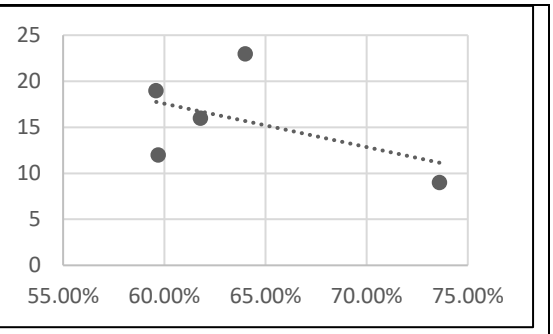


Fig. 2: Paired Comparisons of Percent Homeownership and Recovery Time

4.2 Physical Indicators of Resilience

Before determining if physical indicators of resilience are associated with reduced costs of recovery, two possible interpretations of one measure of the costs of Hurricane Matthew recovery—increased NFIP payments—were considered. For this discussion, increased average NFIP payments are interpreted as being associated with greater damage, increased costs of recovery, and reduced resilience. Data suggest support for the hypothesis that a lower number of mobile homes makes a community more resilient as shown in Figure 3. The presence of fewer mobile homes in a community seems to be associated with a smaller percentage of households receiving damage assistance awards, which suggests increased resilience.

County	Percent Not Mobile	Percentage of household
Robeson	60.90%	21.07%
Bertie	67.40%	8.07%
Columbus	67.50%	12.70%
Wayne	74.70%	6.47%
Lenoir	77.00%	6.52%
Edgecomb	78.10%	8.57%

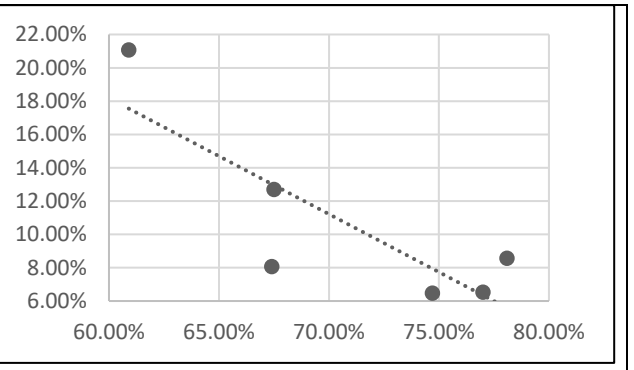


Fig. 3: Paired Comparisons of Percent Not Mobile Homes and Housing Damage Assistance

Data also suggest support for the hypothesis that having completed more road and bridge projects following Hurricane Floyd using FEMA PA funds made a community more resilient (Figure 4). Having completed more road and bridge projects after Hurricane Floyd seems to be associated with having fewer road closures following Hurricane Matthew.

County	Road and bridge projects	Number of road closures
Robeson	3	184
Bertie	4	26
Wayne	5	161
Lenoir	9	60
Edgecom	18	59
Columbus	23	43

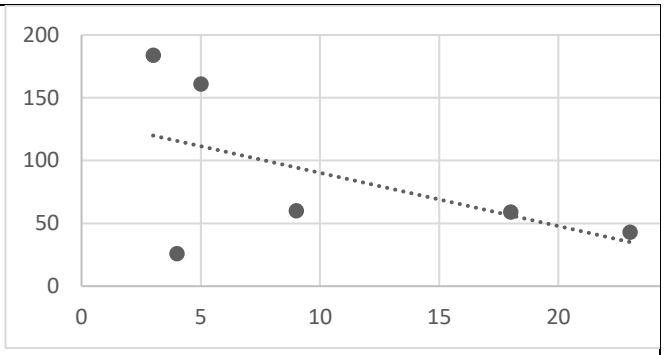


Fig. 4: *Paired Comparisons for Road and Bridge Projects Completed after Hurricane Floyd and Number of Road Closures After Hurricane Matthew*

Composite scores for other disaster management indicators of resilience were also examined relative to the time and costs needed to recover following Hurricane Matthew. However, the six data points were insufficient to draw conclusions about the meaning of the composite scores.

4.3 Losses Avoided Findings

In addition to the exploratory study of resilience described in the previous section, a study to examine the losses that were avoided as a result of the implementation of mitigation measures was performed. For the losses avoided study, the independent variable measures were the dollars spent and locations where the risk of flooding was mitigated prior to Hurricane Matthew through acquisition and demolition of structures, as well as estimated depths of flooding due to Hurricane Matthew. The dependent variable measures were estimates of losses avoided due to having mitigated the risk of flooding. The method used to conduct the losses avoided study was developed by FEMA (2009). The Losses Avoided Study was based on property acquisitions in each county and a qualitative discussion that describes other types of mitigation measures that resulted in unquantified losses avoided. Each of the six study counties has completed a number of acquisitions of flood-prone properties, which involves purchasing the structure and land, demolishing the home, and maintaining the property as open space in perpetuity

Table 7 denotes the number of acquired structures by county where flooding occurred in Hurricane Matthew that would have resulted in building damage had it not been acquired and demolished. To conduct a storm event analysis, the project team reviewed the number of residential structures in each county that were damaged in some way by Hurricane Matthew. The results of the flood inundation analysis describe the estimated depths of flooding in the 1,138 locations where structures were acquired and denotes remaining properties experienced flooding following Hurricane Matthew. Table 7 also shows the dollar value of losses that were calculated to have been avoided in Hurricane Matthew because of the prior acquisitions of flood-prone structures

undertaken following Hurricane Floyd. As shown in Table 7, the total dollar value of losses avoided exceeded $133 million compare to a $116 million investment in hazard mitigation following Hurricane Floyd.

Table 7: Losses Avoided Following Hurricane Matthew

County	Number of Structures[1]	Avoided Building Damages[2]	Avoided Contents Damages[3]	Avoided Displacement Cost[4]	Total Losses Avoided
Bertie	25	$1,859,840	$505,280	$1,037,380	**$3,402,500**
Columbus	10	$908,000	$244,400	$557,836	**$1,710,236**
Edgecombe	170	$10,271,520	$2,824,640	$4,863,940	**$17,960,100**
Lenoir	450	$22,747,360	$6,331,520	$9,072,178	**$38,151,058**
Robeson	87	$6,001,760	$1,638,880	$2,984,913	**$10,625,553**
Wayne	396	$33,028,480	$8,925,440	$19,299,175	**$61,253,095**
				Total	**$133,102,542**

[1] From Table 5-3, these are structures that were acquired and demolished, but would have experienced less than 2, between 2 and 5, or more than 5 feet of flooding during Hurricane Matthew

[2] Multiply number of buildings with less than 2, 2 to 5, and more than 5 feet of flooding by building value ($160,0000) and by percent of structural damage from Table 5-3 and sum for each county.

[3] Multiply number of buildings with less than 2,2 to 5, and more than 5 feet of flooding by content value ($80,000) and by percent of contents damage from Table 5-3 and sum for each county.

[4] Multiple number of buildings with less than 2, 2 to 5, and more than 5 feet of flooding by daily cost of displacement ($217) and by number of days of displacement from Table 5-3 and sum for each county.

5. Conclusions, Study Limitations, and Recommendations

The findings of this study are consistent with other studies and suggest that better data, particularly those associated with the outcomes of a storm at the local rather than state level, will provide better opportunities to empirically examine resilience theory. It is also clear that hazard mitigation investments tied to the acquisition of flood prone

properties makes a difference in advancing resilience as the investment of over $116 million in hazard mitigation through property acquisitions following Hurricane Floyd saved approximately $133 million in potential damages following Hurricane Matthew. The return on investment (ROI) is expected to increase through time because the region in which the study counties are located regularly experiences hurricanes or tropical storms. With each hurricane, the ROI will increase due to the accumulation of losses avoided.

5.1 Study Limitations

As an exploratory study, the findings are not statistically valid because they are based on a sample of only six counties. The findings presented in this report cannot be used to infer those one or more indicators of resilience led to a reduced recovery time or reduced costs of recovery. Additionally, as an exploratory study, findings are based on comparisons of only two factors. Potentially associated conditions or factors were not considered simultaneously, as would have happened if the sample size was large enough to use a multiple linear regression research approach. Furthermore, the indicators were not weighted.

Some difficulties encountered in measuring pre-hurricane conditions were similar to those encountered when analyzing other social phenomena, to include determining the unit of analysis and obtaining accurate data. The initial study sample included six small municipalities. However, it proved difficult to find measures of many of the theoretical indicators of resilience. Some of the data available through FEMA's Hazard Mitigation Assistance database were not connected to specific acquired properties but rather to grant awards involving the acquisition of several properties. A primary difficulty encountered when measuring pre-hurricane conditions involved data accuracy. It was difficult to find data that were comparable across the six sample counties. Data found in local plans, reports, or other documents were not necessarily comparable across communities and counties. Reports included data for different size areas, and the methods used for gathering the data are not necessarily recorded.

Challenges encountered in measuring post-hurricane conditions were due in part to the approach used to gather data and in part due to the timeframe in which this study was conducted. Local officials of the six study counties were contacted by email and asked questions about Hurricane Matthew outcomes. However, it was not possible to determine long-term impacts of Hurricane Matthew because the study was undertaken approximately 17 months after Hurricane Matthew occurred. Monitoring and assessing progress toward building more resilient communities is a stated aim of the Disaster Mitigation Act of 2000 planning requirements.

5.2 Recommendations

The ability to assess progress towards the laudable goal of creating more resilient communities requires the systematic collection and sharing of relevant data by federal, state, and local government agencies. The failure to do so means that the programs, policies, and plans touting resilience remains largely aspirational and the actions taken remain disconnected to explicit, measurable outcomes. Conversely, the ability to

develop and utilize sound, measurable resilience indicators allow governmental decision makers at all levels to better assess whether their policies, programs, plans, and investments are furthering resilience goals.

Thus, how can we codify the means by which the systematic collection and sharing of data occurs and assign responsibility for the collecting and sharing of the information in a manner that can inform resilience policy? This issue represents both a technical and administrative challenge that requires the attention of federal, state, and local levels of government. This question also requires the thoughtful inclusion of an equity lens as smaller, under resourced communities often struggle to capture and use this type of information to inform their decision-making processes. Therefore, any effort to develop useful resilience indicators must confront the questions surrounding the ability to access and interpret resilience indicator data.

As more relevant empirical data are collected and analyzed, the number of potential indicators of resilience can be reduced to those that have been shown to be effective in reducing the amount of time, level of effort, and costs required to recover from a disaster. Such information will ultimately allow communities to focus their bounded resources on taking actions that are most effective in improving resilience.

6. Key Themes, Questions, and Additional Readings

6.1 Key themes

This study hypothesized that higher indicators of resilience would lead to less damage sustained by privately owned structures and public infrastructure and that the time required to recover would be reduced. Key themes that emerged from this study were:

- A lower percentage of low- to moderate-income households makes a community more resilient.
- A higher percentage of homeownership makes a community more resilient.
- A lower percentage of mobile homes makes a community more resilient.
- A larger number of road and bridge projects completed after Hurricane Floyd (measured as completed with FEMA Public Assistance funding) made communities more resilient than communities with fewer projects completed.

6.2 Discussion questions

- How is resilience defined by the disaster research community? Is there consensus on the indicators for measuring resilience?
- How do social and economic resilience fit into disaster resilience and risk reduction? What are some of the key factors?
- What types of mitigation actions are typically taken by state and local authorities to reduce hurricane risks?
- What types of research methods can be employed to support an empirical study of this nature?

- Describe the resilience assessment framework used by the researchers? Discuss some fo the key findings from their analysis?
- What were some of the limitations of their study? Summarize any recommendations?
- This publication presented a case study of areas effect by Hurricanes Floyd and Matthew in North Carolina. What case studies can you think of for the area where you live?

6.3 Additional Readings

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Optimizing resilience planning with community-oriented adaptation decision support tools: FloodAdapt Case study of Charleston, SC

Kathryn Roscoe, Tony Minns, Edwin Welles, Claire Jeuken[41]

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Abstract

Climate adaptation planning requires understanding how floods and impacts will change in the future, and how and where adaptation options and policy decisions will alleviate those impacts. Recent advances in the speed and accuracy of compound flood and impact models make it possible to assess the many scenarios needed to facilitate adaptation planning, but these advances have remained out of reach for decision-makers and planners. The research and development described in this paper focused on bridging the gap between scientific advances and practitioner needs through the creation of a FloodAdapt community flood resilience support system (CFRSS) that would be freely available to all coastal communities in the U.S. FloodAdapt CFRSS was designed and iteratively developed in close collaboration with the Department of Homeland Security and the City of Charleston, focusing on user needs, user friendliness, accuracy, and visualization. This approach led to a tool that city staff are comfortable and excited to use to evaluate flooding and impacts for different (compound) events, projections about the future, and interventions to alleviate flood risk. FloodAdapt CFRSS use was demonstrated in Charleston, addressing adaptation planning-related questions that are expected to resonate with a wide user audience, to serve as guidance for other communities. FloodAdapt CFRSS is an important first step in bringing scientific advances to the decision-makers who need them. Future R&D aims to advance the design and accessibility of the tool, expand the interventions that can be assessed, and integrate social vulnerability information to support equitable decision-making.

Keywords

Climate Adaptation, flood resilience, decision support, FloodAdapt

1. Introduction

"When it comes to [flooding and sea level rise], we're going to have to choose innovation over business as usual."[42]

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Deltares
e-mail: Kathryn.roscoe@deltares.nl, Tony.minns@deltares.nl, Edwin.welles@deltares-usa.nl, Claire.jeuken@deltares.nl

[42] Eric Letsinger (Quantified Ventures) during his presentation at the 2019 AFCMayorsSummit.

Making decisions on climate adaptation and resilience relies on understanding how floods and impacts will change in the future under changing climate and socio-economic conditions, and how and where adaptation options and policy decisions will alleviate those impacts. Compound flood and impact modeling is essential for answering community questions that are at the heart of any planning effort. Questions like: *How will potential adaptation options reduce flood impacts? How will those options perform for different types of events, like hurricanes, king tides, or heavy rainfall? Which neighborhoods will benefit most? How will those options hold up in the future?* The ability to answer such questions and gain the understanding needed for good decision-making is typically hindered by the cost of procuring flood and impact modeling studies, and by time-consuming model simulations which limit the number of scenarios that can feasibly be considered within the scope of such studies. Recent years have seen significant improvements in the availability and speed of accurate compound flood modeling ((Bates, et al., 2020) (Leijnse, Ormondt, Nederhoff, & Dongeren, 2020) (Nederhoff, et al., 2021)). These improvements make it possible to simulate a far greater number of scenarios and therefore answer far more community questions, but these achievements have remained disconnected from practitioners, planners, and decision-makers.

The research and development challenge that was addressed in this initiative was to take the latest in fast, free, accurate compound flood and impact modeling software, and build these into a decision support system that would remove the information barriers for planners and decision-makers. The goal was to create a tool that non-modelers would be able to operate to answer a wide variety of adaptation- and planning-related questions. To support this objective, the development team worked very closely with DHS Science and Technology Directorate (DHS S&T) and with the City of Charleston as an end-user community, from the very inception of the initiative. Regular testing of the developments by the City of Charleston supported an iterative design process that ensured the decision support system would be aligned with the needs and capabilities of city staff. The developed support system is currently titled: FloodAdapt, Community Flood Resilience Support System (CFRSS), or FloodAdapt CFRSS.

2. FloodAdapt CFRSS Overview and Components

The FloodAdapt CFRSS is a *community* flood resilience support system, and the needs of the community are central to the system design and functionality. It is built to answer questions community decision-makers and stakeholders will ask about potential flood scenarios, equity, the effectiveness of measures, or impacts of future changes. Figure 1 provides a high-level overview of the FloodAdapt, its components, and the connection with stakeholder and decision-maker questions.

Community-oriented questions are translated into *scenarios* through the FloodAdapt user interface. Scenarios are defined in the FloodAdapt CFRSS as a

combination of a future *projection* (like sea level rise or economic growth), a hydro-meteorological *event* (like a king tide with heavy rainfall or a hurricane), and a *strategy* (like a sea wall with homes elevated outside the protected area).

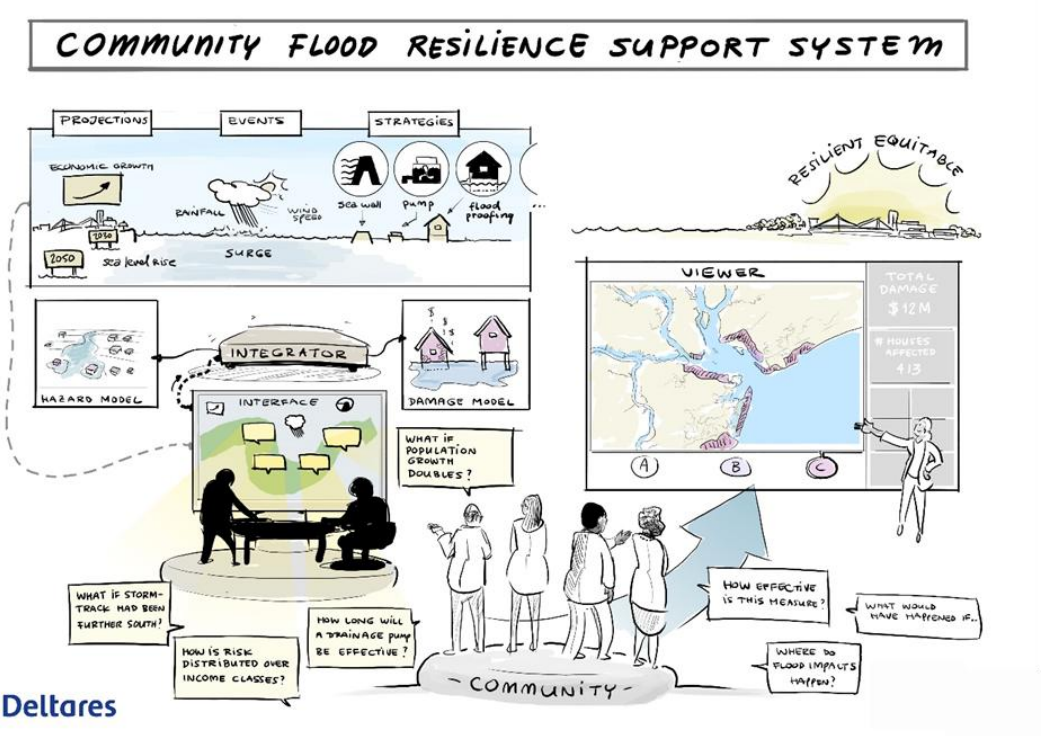


Fig. 1: *Illustration of the components of the FloodAdapt CFRSS, of which the community is central*

The user interface allows users to define different types of synthetic or historic hydro-meteorological events, specify future projections, and "implement" adaptation options, including home elevations, buyouts, floodproofing, sea walls, levees, and pumps. The user can further define strategies as combinations of measures, such as a sea wall together with home elevations outside the protected area. Via the user interface, the user can define scenarios as combinations of the events, projections, and strategies they have built. For example, a scenario could be a king tide (event) with 1 foot of sea level rise (projection) and home elevations in a specified area (strategy). A screenshot of the user interface is shown in **Figure 2**.

The scenarios are fed to the core of FloodAdapt CFRSS – the *integrator*. The integrator automatically translates the user-selected projection, event, and strategy into the required changes in the flood model and damage model inputs. For example, if a user wants to raise homes, they only need to select these homes in the user interface, or draw a polygon around an area, and the integrator automatically modifies the building exposure file to increase the elevations of those selected homes. If the user draws a flood wall, the integrator modifies the flood model input file to include the coordinates and elevation of the new flood wall. This means that once the flood and

damage models are set up, the users do not need to be experienced modelers to perform simulations and explore the flooding and impacts for a range of scenarios.

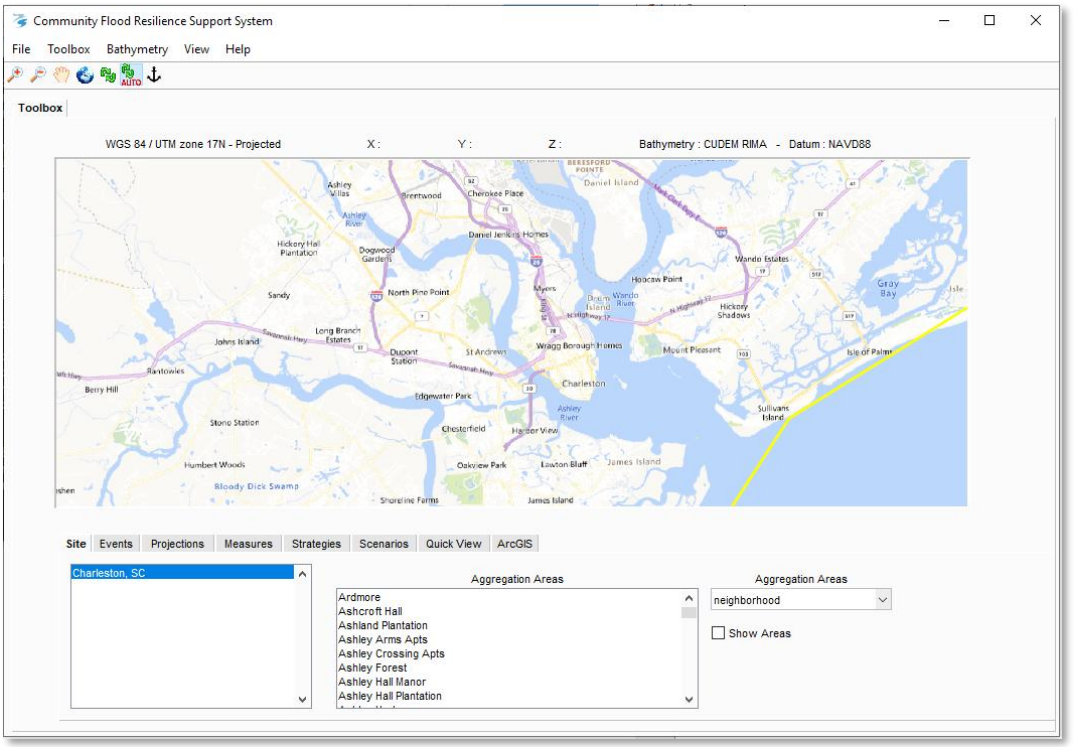


Fig. 2: *The CFRSS user interface, containing tabs to define events, projections, measures, strategies, and scenarios; the Quick View and ArcGIS tabs provide visualization of the simulated scenarios.*

The computation speed of the flood and damage models in the FloodAdapt CFRSS is a key feature that helps remove the modeling bottleneck in resilience planning. The physics-based compound flood model in the FloodAdapt CFRSS is the Super-Fast Inundation of Coastal Systems (SFINCS) model[43], a hydraulic model developed at Deltares and freely available[44]. SFINCS can accurately predict compound flooding due to surge, rainfall, and river discharge, and at a fraction of the computation time typically required by physics-based models. The damage model is the Deltares-developed flood impact assessment tool (Delft-FIAT). Delft-FIAT calculates the flood damages to individual buildings and roads, and – when social vulnerability data is available – aggregates these damages over vulnerability classes. Computation times vary based on factors like computer speed, model extent and domain, or grid size, but in general they run on the order of a couple of minutes per scenario.

[43] Tim Leijnse, Maarten van Ormondt, Kees Nederhoff, Ap van Dongeren, Modeling compound flooding in coastal systems using a computationally efficient reduced-physics solver: Including fluvial, pluvial, tidal, wind- and wave-driven processes, Coastal Engineering, Volume 163,2021, https://doi.org/10.1016/j.coastaleng.2020.103796

[44] https://sfincs.readthedocs.io/en/latest/

FloodAdapt CFRSS is coupled to ArcGIS Pro. This allows a user to select scenarios they have simulated, and the CFRSS will prepare a pre-formatted ArcGIS project file that spatially displays flood depths, damages at asset level, inundation on roads, and aggregated damages. The user can also choose to upload scenarios to ArcGIS online, and the FloodAdapt CFRSS will provide a link where the user can view maps of the flooding and damages using the ArcGIS experience builder. The experience builder file is configurable, so the user can tailor the metrics and visuals to tell their own story.

To evaluate adaptation options, it is important to assess how those options perform over a wide range of event types that can impact a community. These include high-frequency, lower-impact events like king tides and heavy rainfall as well as low-frequency, high-impact events like hurricanes. A powerful feature of the FloodAdapt CFRSS is that users can run scenarios with probabilistic event sets and the FloodAdapt CFRSS will automatically calculate and output return period flood maps and damages, expected annual damages (risk), and a spatial flood frequency map, for the user-selected projection and strategy. Setting up the probabilistic (compound) event set is described in detail as an appendix in the FloodAdapt CFRSS user manual[45].

3. Demonstration of the CFRSS in Charleston, S.C.

This section describes a demonstration of the FloodAdapt CFRSS to provide a more concrete understanding of how FloodAdapt CFRSS can be used to answer a wide array of adaptation planning-related questions. We demonstrated the use of FloodAdapt CFRSS in Charleston, South Carolina, in close collaboration with the City of Charleston, addressing relevant questions that are expected to resonate with a wide user base. While the questions addressed in the demonstration are realistic, it is important to note that they do not represent specific planning choices of the City of Charleston; they were selected for demonstration purposes. In this section we demonstrate the use of both single-event scenarios and probabilistic event-set scenarios in the FloodAdapt CFRSS. Figure 3 shows the questions addressed in this section[46].

[45] For details on setting up the probabilistic event set, see: https://www.deltares.nl/app/uploads/2022/07/Community-Flood-Resilience-Support-System-User-Manual.pdf#page=84

[46] The community questions in this paper are aligned with a tutorial video available at the following link: https://vimeo.com/727017820/e8d7f104a7. The reader can follow the tutorial to learn the steps required in the CFRSS to reproduce the results presented here.



Fig. 3: *Planning-related questions that will be addressed in this chapter using the FloodAdapt CFRSS.*

For each of the questions addressed, we focus on two neighborhoods in Charleston: Rosemont, a lower-income neighborhood in the neck of the peninsula, and South Windermere, a higher-income neighborhood in West Ashley which is particularly vulnerable to flooding; see Figure 4. The FloodAdapt CFRSS calculates flooding, impacts, and risk for the entire greater Charleston area. However, focusing on neighborhoods allowed us to zoom into the results and show the level of detail possible with the FloodAdapt CFRSS, in which individual road segment outages and impacted buildings can be viewed. The FloodAdapt CFRSS calculates and gives damages and risk in dollars, both at the building level and at aggregated levels; however, for privacy reasons, we have displayed damage and risk information in the following examples in terms of qualitative categories, like “low”, “medium”, and “high”.



Fig. 4: *Map of the Charleston area, highlighting two focal neighborhoods – Rosemont and South Windermere – used to demonstrate the utility of the CFRSS.*

3.1 King Tides are a problem now – how will that look with sea level rise?

To answer this question, we looked at two scenarios, both of which use the November 2021 king tide as the event. For the first scenario we consider current conditions (current sea level), and for the second scenario we consider a sea level rise of 1 foot above current levels (see figure 5 below).

Event	Projection	Strategy	
King tide	Current conditions	No measures	Scenario 1
King tide	SLR = 1 foot	No measures	Scenario 2

Fig. 5: *King Tide Scenarios*

Once the user inputs these scenarios, FloodAdapt CFRSS calculates maximum flood depth map and flood impacts for both scenarios. This calculation can take between 2-10 minutes per scenario, depending on the speed of the computer. Figure 6 shows the flooding for the November 2021 king tide event (Scenario 1), with the two focus neighborhoods indicated. FloodAdapt CFRSS produces flood maps and shapefiles of damages, which are stored locally on the user's computer. The user interface also includes a "create project" button that allows the user to automatically generate a formatted ArcGIS project file with all results loaded.

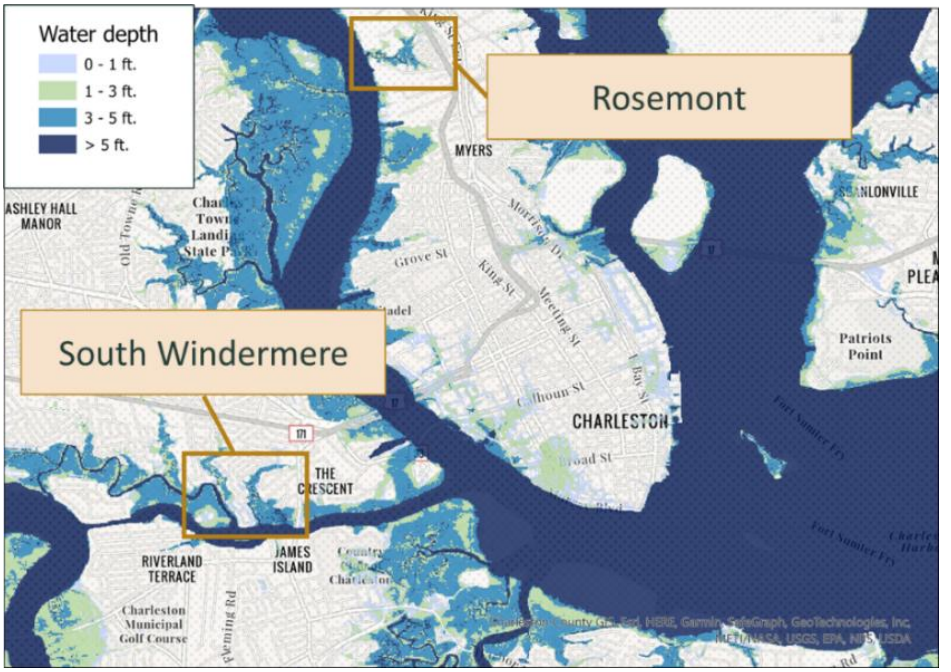


Fig. 6: *November 2021 king tide flooding in Charleston, modeled with the CFRSS. Zoomed-in flooding at the focus neighborhoods is presented in the following figures.*

Figure 7 and Figure 8 show the flooding and impacts for current conditions and with 1 foot of sea level rise zoomed in to the Rosemont and South Windermere neighborhoods. This assessment brought the realization that the Rosemont neighborhood is not imminently vulnerable to king tide flooding, and furthermore, that road flooding in the South Windermere neighborhood will be serious in the future, and even homes will be impacted by king tide events without any interventions in place.

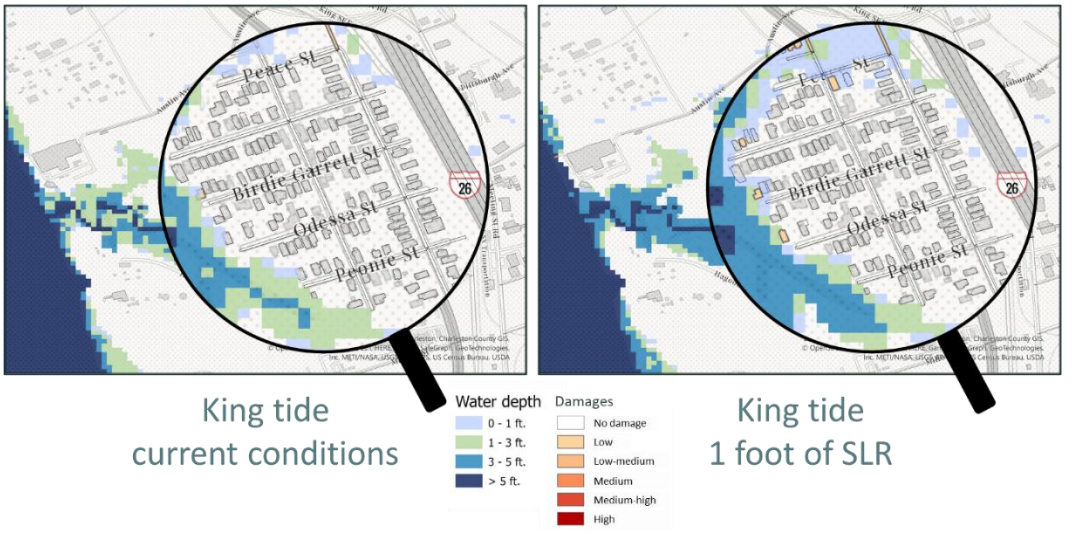


Fig. 7: *November 2021 king tide flooding, zoomed in to the Rosemont neighborhood. Image on the left with current conditions. Image on the right with 1 foot of sea level rise.*

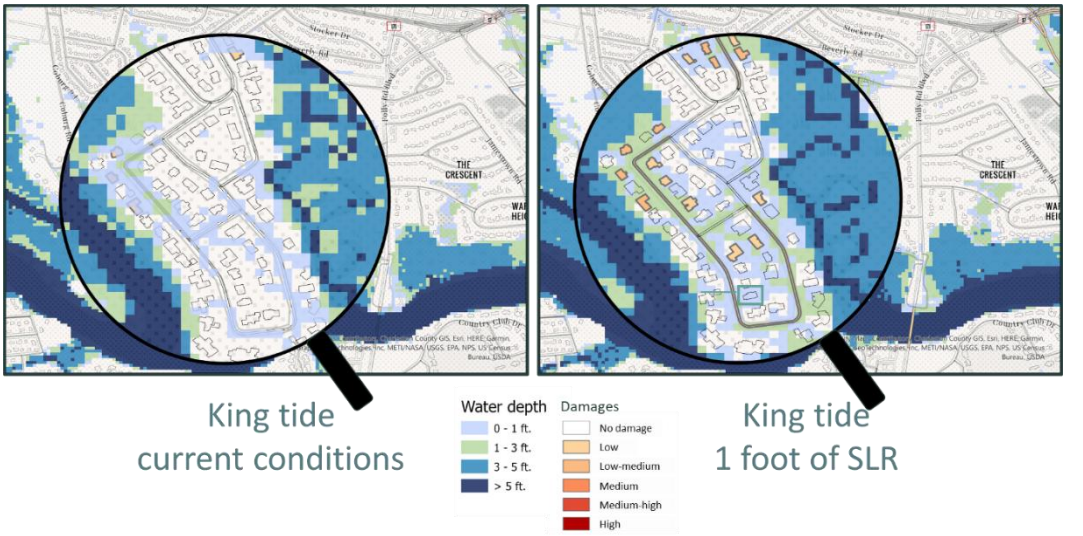


Fig. 8: *November 2021 king tide flooding, zoomed in to the South Windermere neighborhood. Image on the left with current conditions. Image on the right with 1 foot of sea level rise.*

3.2 There is a plan for the peninsula – what about the rest of Charleston?

The US Army Corps of Engineers (USACE) has investigated a seawall around the Charleston peninsula that would be elevated to 12 feet above NAVD88 (USACE, 2022). This would protect a large portion of the peninsula from coastal storm surges and tidal flooding, but areas outside the peninsula were not included in the modeling efforts. This question asks how the rest of Charleston city will be affected by the extreme hurricanes that the peninsula will be protected against.

To address this question, we looked at a synthetic hurricane event that would result in a 12-foot water level at the Charleston gauge, relative to the NAVD88 datum. The scenario components are shown below in Figure 9.

Event	Projection	Strategy
12-foot surge + tide	Current conditions	No measures

Fig 9: *Scenarios Components for Synthetic Hurricane Event in Charleston, S.C.*

The FloodAdapt CFRSS calculates in this scenario the flooding and flood impacts throughout the City, allowing the user to zoom in on any area of interest. We continue to focus on the Rosemont and South Windermere neighborhoods, both of which would not be protected by the seawall, for illustration. The flooding and flood impacts calculated with the FloodAdapt CFRSS are shown in **Figure 10** for the Rosemont neighborhood and **Figure 11** for the South Windermere neighborhood. Both neighborhoods would experience substantial impacts in this event.

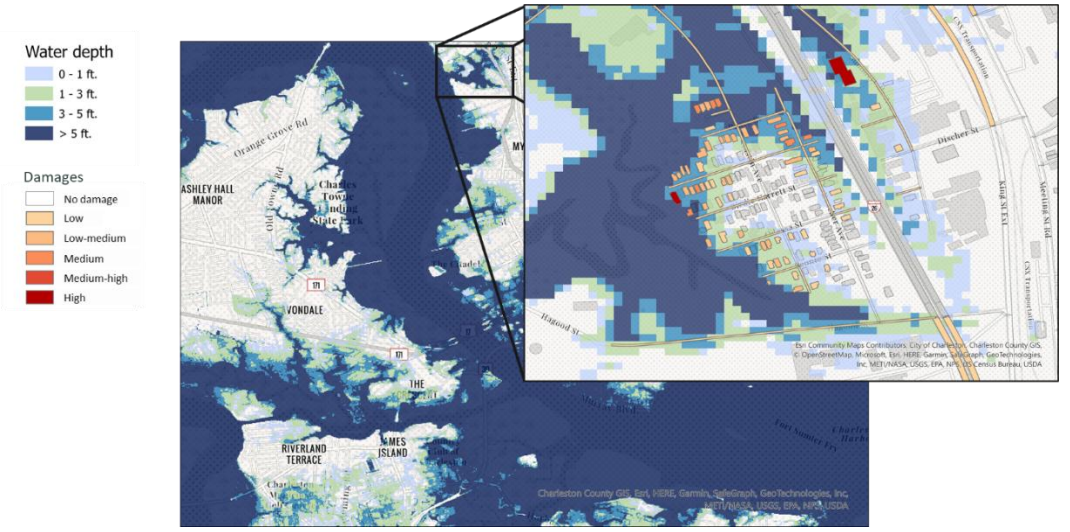


Fig. 10: *Flood depths and damages for the 12-foot event for the entire Charleston City, zoomed in here to the Rosemont neighborhood.*

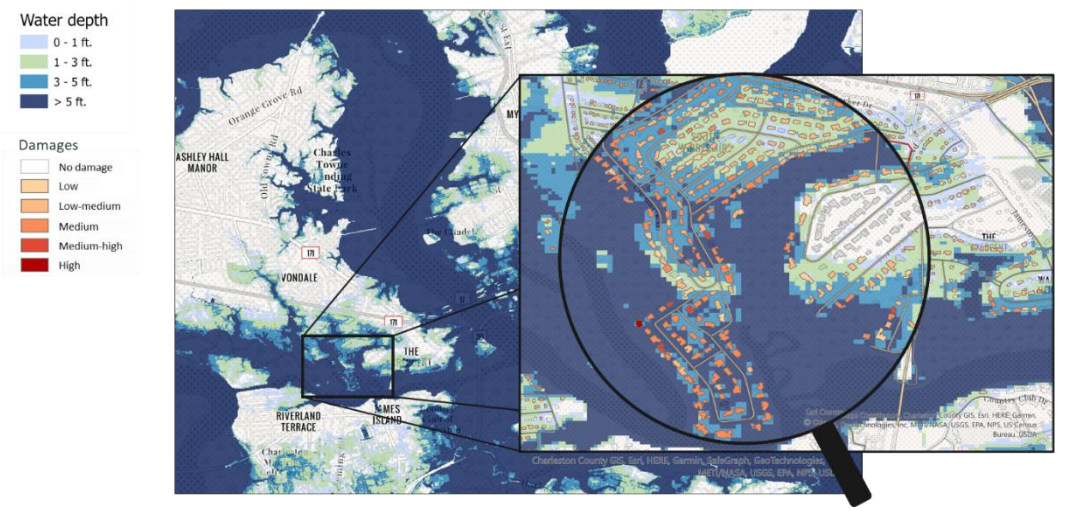


Fig. 11: *Flood depths and damages for the 12-foot event for the entire Charleston City, zoomed in to the South Windermere neighborhood.*

3.3 What measures can we take to mitigate and protect ourselves?

The impacts observed in the previous section led to follow-up questions about solutions: 'What if homes in the Rosemont neighborhood were elevated to the same level as the peninsula sea wall?' and 'What if homes in the north part of South Windermere were elevated to one foot above base flood elevation and homes in the southern part of South Windermere would be bought out?' To answer this question, we ran two scenarios (see Figure 12 below) – one with the 12-foot event and no measures and one with the same event, with homes elevated and partially bought out in South Windermere.

Event	Projection	Strategy	
12-foot surge + tide	Current conditions	No measures	Scenario 1
12-foot surge + tide	Current conditions	Elevations and buyouts	Scenario 2

Fig. 12: *Windermere Neighborhood Scenarios*

The Rosemont measures are based on proposed solutions by the USACE, but the South Windermere measures are for illustration purposes only and not currently part of any plans. We showed the damages both with these interventions and without to visualize the damage reduction for the extreme 12-foot event (see **Figure 13** for

Rosemont results and **Figure 14** for South Windermere results). For the Rosemont neighborhood, elevating homes was effective and almost no buildings were damaged. However, the road flooding for Rosemont was not addressed by this solution and the neighborhood would be isolated in this event. For South Windermere, the damages were greatly reduced; many elevated homes did still experience damages, but because this event is so extreme, these single-event results do not portray a complete picture of how the measures would perform overall.

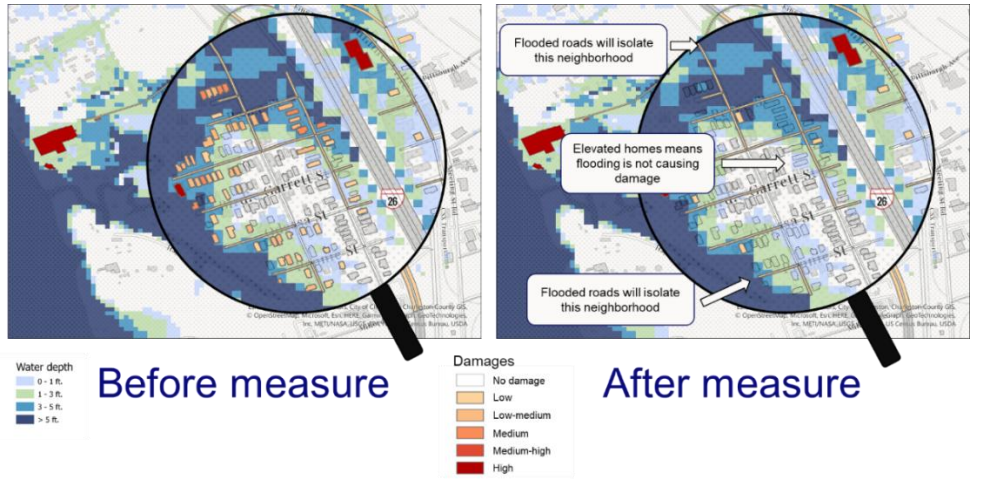


Fig. 13: *Flood depths and damages for the 12-foot event in Rosemont before and after elevation and buyout interventions.*

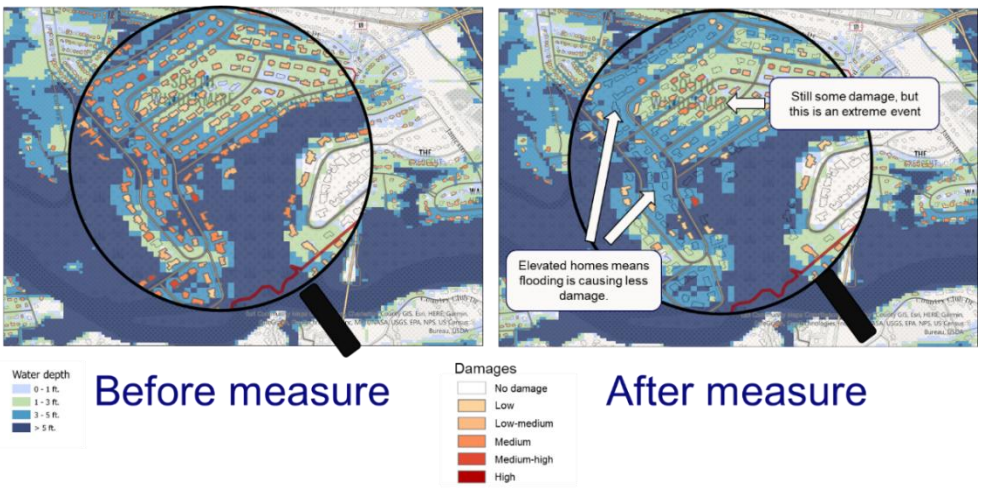


Fig. 14: *Flood depths and damages for the 12-foot event in South Windermere before and after elevation and buyout interventions.*

3.4 How effective are measures considering the full range of events affecting the City?

For this question we used a set of 200 compound events[47], both hurricane and non-hurricane, to determine the expected annual damages (risk). Risk reduction is assessed by comparing the expected annual damages resulting from two scenarios: the probabilistic event set with no measures, and the probabilistic event set with the elevations and buyouts (see scenarios in Figure 15 below).

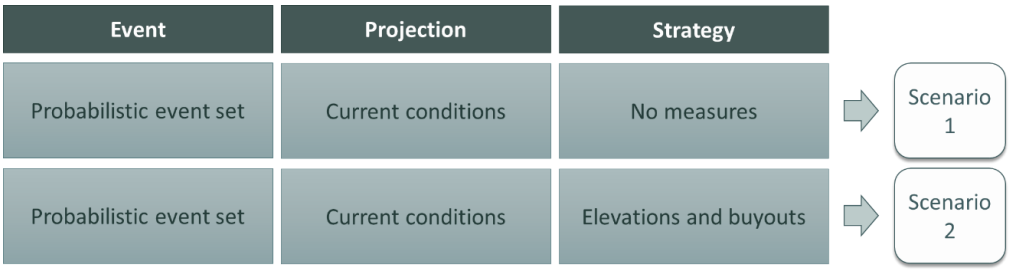


Fig. 15: *Probabilist Compound Event Planning Scenario using Current Conditions*

Figure 16 shows the neighborhood-level expected annual damages before and after implementation of the measures. We continue to focus on South Windermere and Rosemont to present the results both with and without the considered elevation and buyout interventions. While the elevated homes in South Windermere were impacted by the extreme 12-foot event, they lowered the expected annual damages to a low level when considering a full range of flood events and the likelihood of those events. The elevated homes in Rosemont, where measures performed well even with the extreme 12-foot event, showed almost no risk to buildings when considering the full range of flood events.

[47] For details on setting up the probabilistic event set, see: https://www.deltares.nl/app/uploads/2022/07/Community-Flood-Resilience-Support-System-User-Manual.pdf#page=84

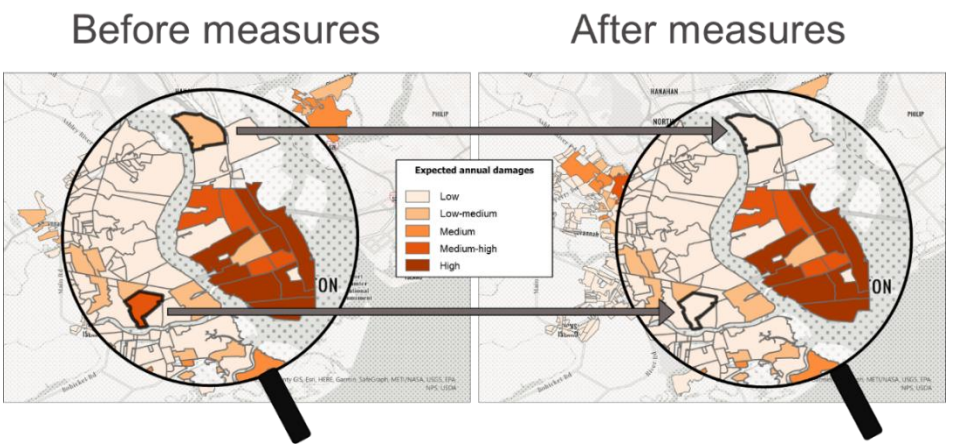


Fig. 16: *Neighborhood-level expected annual damage, before and after interventions in Rosemont (top arrow) and South Windermere (bottom arrow).*

3.5 How well will these measures hold up under sea level rise?

To evaluate how well the measures will hold up under sea level rise, three scenarios were run in the FloodAdapt CFRSS, all of which used the probabilistic event set and the strategy of elevations and buyouts in Rosemont and South Windermere. The first used a projection of current conditions (no sea level rise), the second used a projection of 1 foot of sea level rise, and the third used a projection of 2 feet of sea level rise. See Figure 17 below the components of the three scenarios.

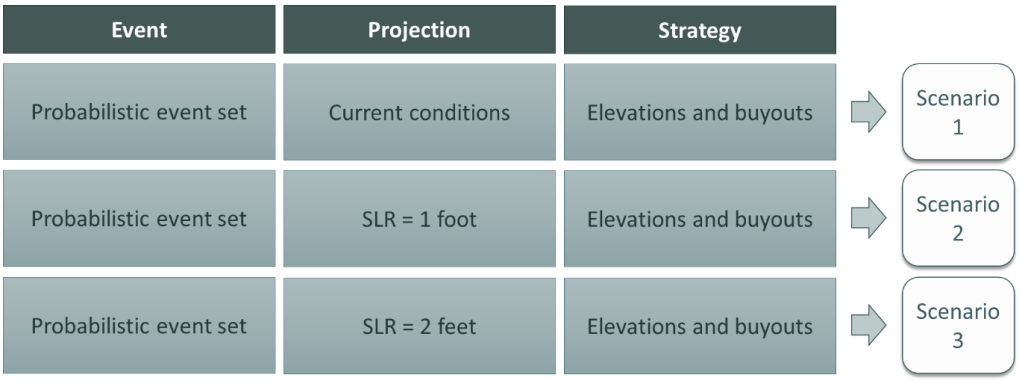


Fig. 17: *Probabilistic Compound Event Scenarios with Current Conditions and See Level Rise of 1 or 2 feet.*

In South Windermere, the risk to many homes will increase as sea levels rise, indicating that an elevation higher than 1 foot above base flood elevation may be a more sustainable choice (see **Figure 18**). In Rosemont, the homes remained very low

risk (see **Figure 19**, indicating that if the flooded roads which isolate the neighborhood could be addressed, this would be a sustainable solution for the Rosemont neighborhood.

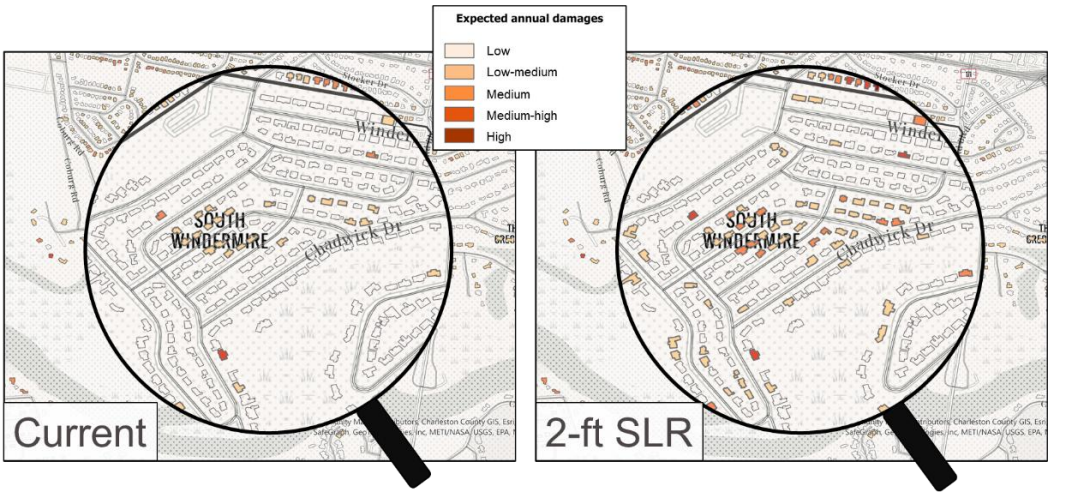


Fig. 18: *Expected annual damages with elevation and buyouts implemented in South Windermere for the current situation (left) and 2 feet of sea level rise (right).*



Fig. 19: *Elevated homes lead to sustained risk reduction in Rosemont; expected annual damages for the current situation (left) and 2 feet of sea level rise (right).*

4.0 Findings and Future Research

The community flood resilience support system developed in this project is a model-based decision support system intended to accelerate climate adaptation by making it easier for local and regional agencies to understand their flood risk under different scenarios. The FloodAdapt CFRSS empowers technical non-modelers to evaluate the flooding and impacts for a variety of events, projections about the future, and possible mitigation and adaptation measures. This project has demonstrated that the results of the FloodAdapt CFRSS were realistic, accessible, and understandable to the end-users. Through workshopping with end-users, we have demonstrated the performance of the FloodAdapt CFRSS for different event types: surge, tide, and rainfall events, and included compound events like hurricanes.

Throughout the development, frequent engagement with the City of Charleston and DHS S&T helped improve the FloodAdapt CFRSS and shape the future research and development path. The amount of valuable feedback we obtained is too voluminous to include in its entirety, so we highlight here a few examples of important suggestions for possible *future development* of the FloodAdapt CFRSS.

- Usability of the tool
  - Inclusion of NOAA rainfall curves for synthetic events
  - Replacing the sea level rise projection, currently in terms of feet, with a drop-down sea level rise scenario selector, and a box to indicate the year of interest
  - Inclusion of several 'standard' events – like a recent king tide, historic hurricane, or design rainfall event – that users can choose for fast evaluation.
- Tailoring output to planning needs
  - In addition to risk and damage maps, output a map showing the probability of experiencing flood damage within a typical mortgage term of 30 years
  - Output a flood frequency map, to evaluate where nuisance flooding may become intolerable in the future as sea levels continue to rise
  - Create a dashboard with important metrics for a scenario – like number of homes impacted, dollar amount of damage, or number of impassable roads – so a user does not need to manually find the results in Excel files on their computer.
- Evaluating adaptation options
  - Include green infrastructure solutions for rainfall nuisance flooding
  - Include coastal nature-based solutions
  - Include a simplified way to represent drainage infrastructure improvements
- Support equity in adaptation planning
  - Post-process results to show impacts of future changes and adaptation options on flooding and impacts to the most vulnerable
  - Show metrics to evaluate the livability for vulnerable community members – e.g. output the number of vulnerable homes impacted in frequent events

- Output damages as a fraction of the maximum potential value of the home, to represent damages more evenly across income classes (low damages to a poorer home would be equivalent to much larger damages for a wealthier home)

The input from Charleston and DHS S&T led to the defining of key objectives that will be addressed in future phases of development of the FloodAdapt CFRSS. These are:

(1) improved user experience, including updated graphical user interface and support for the initial setup of the FloodAdapt CFRSS base models, using national, global, or locally-accessible datasets, to support a broad uptake and ease of implementation of the FloodAdapt CFRSS.
(2) expanded and improved functionality to support climate adaptation planning, such as including additional adaptation options in the system, or support for calculating benefits or adaptation tipping points of adaptation options.
(3) expanded and improved support of equitable decision-making, in terms of providing guidance on the incorporation of vulnerability data, outputting information about the impacts to vulnerable members of the community in terms of metrics that allow the community to evaluate their equity targets and using vulnerability data to more equitably calculate the costs and benefits of adaptation options, including the social cost of carbon.

As a representative of the target audience for the decision-support system, the City of Charleston also served as an indicator how successful the initiative was. Engagement sessions in the final phases of the project elicited user feedback on the utility and potential of the system for their planning processes. **Figure 20** shows some of the positive feedback that was given on the high potential of FloodAdapt CFRSS. Thereunder are some positive end user quotes from city representatives during the May 2022 City Council meeting (see figures 21 below).



Fig. 20: Feedback from City of Charleston staff members

"This is fascinating, and I can see the uses are going to be incredible. We've got some incredible minds working behind us."

– Charleston, S.C. Council member Michael Seekings

"You can come up with your own scenarios, for your own neighborhood or any part of the city – 'what if such-and-such happened?' – and be able to see the impacts that can happen to our community. Charleston is really blessed that we were able to partner with them to create this amazing tool."

– Charleston, S.C. Mayor John J. Tecklenburg

Fig 21: End user Quotes from Charleston, S.C.

5. Key themes, discussion questions, and additional readings

The FloodAdapt CFRSS was developed to support adaptation and resilience planning, to provide community understanding of the flooding and impacts resulting from different scenarios of interest, to understand the urgency of actions in different areas, to prioritize investments, and to assess the effectiveness and longevity of different adaptation options. It has provided a valuable first step towards empowering communities to address the planning issues and themes important to them.

5.1 Key themes

Key themes that emerged during the FloodAdapt CFRSS initiative were:

- Co-creating with end-users from the inception of development to ensure a tool that end-users will understand and be excited to use
- Bridging the gap between modeling and end-users, making the latest technological advances in compound flood and impact modeling accessible to planners and decision-makers
- Evaluating which output is meaningful for different stakeholders, such as number of homes impacted in a particular scenario, or frequency of road flooding
- Understanding end-user needs allows for often minor post-processing that can lead to significant improvements in user experience, like automatic summing up of damages over low-income homes
- Empowering local community agencies to be able to evaluate flooding, impacts and risk for scenarios they are interested in

5.2 Discussion questions

- What do you consider to be important objectives when preparing a climate adaptation plan?
- What kind of questions would you want a system like the FloodAdapt CFRSS to help you answer?
- What kind of output would you want to use to evaluate adaptation options?

- What kind of information would you want to share with the public? What message would you want to convey?
- This publication presented use cases – in the form of community questions – for the City of Charleston. What use cases can you think of for the area where you live?

5.3 Additional Readings

- FloodAdapt CFRSS user manual – includes comprehensive information on the setting up and use of the FloodAdapt CFRSS, plus a chapter dedicated to demonstrating how the FloodAdapt CFRSS can be used for adaptation planning: https://www.deltares.nl/app/uploads/2022/07/Community-Flood-Resilience-Support-System-User-Manual.pdf
- FloodAdapt CFRSS tutorial – walks the viewer through the use of the FloodAdapt CFRSS to replicate some of the cases demonstrated in Charleston: https://vimeo.com/727017820/e8d7f104a7
- SFINCS user manual – provides background information about the innovative compound flood model within the FloodAdapt CFRSS: https://sfincs.readthedocs.io/en/latest/
- Delft-FIAT user manual – provides information on the fast and flexible flood impact model within the FloodAdapt CFRSS: LINK TO BE ADDED ASAP
- Charleston City Plan – provides context for some questions that were used to demonstrate the FloodAdapt CFRSS: https://www.charlestoncityplan.com/
- USACE Charleston Peninsula Study – describes the USACE plan for the flood wall around the Charleston peninsula, which provides context for some of the questions used to demonstrate the FloodAdapt CFRSS in Charleston: https://www.sac.usace.army.mil/Missions/Civil-Works/Charleston-Peninsula-Study/

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Section 4

Closing the Flood Insurance Gap and Improving Financial Preparedness

Even with the decades of progress in flood mapping, modeling, and public education, the United States remains acutely underinsured against flood risk. The widening gap between exposure and financial protection, the so-called *protection gap*—continues to jeopardize both household security and the national capacity for timely, equitable disaster recovery. Section 4 confronts this foundational vulnerability head-on, examining the behavioral, structural, and institutional forces that have allowed underinsurance to persist in flood-prone communities.

This section reframes insurance not simply as a financial product but as a *cornerstone of disaster resilience*. Insurance shapes household recovery trajectories, influences rebuilding choices, and reduces reliance on federal disaster aid. When uptake is low, the consequences ripple outward: disasters become more expensive, recovery more inequitable, and long-term resilience harder to achieve. While the National Flood Insurance Program (NFIP) remains essential, it faces persistent challenges related to affordability, risk communication, and geographic penetration—especially in high-risk, socially vulnerable areas. Private-sector innovation has emerged in recent years, but uptake remains fragmented, trust in products is uneven, and major gaps endure.

Section 4 explores these complex dynamics through multiple, intersecting lenses. The opening chapter investigates *risk perception and household decision-making,* drawing on extensive research supported by DHS S&T to understand why so many at-risk residents forgo insurance coverage. The analysis surfaces critical behavioral drivers, limited awareness, cognitive biases, skepticism about value, and competing financial priorities—all of which undermine insurance uptake despite rising risk. These insights are foundational for designing more effective risk communication, outreach campaigns, and incentive structures.

The section then turns to a *policy-centered critique of the NFIP*, examining how structural features such as pricing, mapping, and subsidy design influence both perceived and actual accessibility. Authors assess the implications of FEMA's transition to *Risk Rating 2.0*, weighing its promise of actuarial fairness against concerns about affordability and equity. This analysis invites a broader conversation about the tension between financial sustainability and social responsibility within public insurance programs.

Expanding beyond the federal program, subsequent chapters explore *alternative and*

complementary models aimed at closing the protection gap. These include catastrophe bonds, community-based parametric insurance, and layered risk-transfer mechanisms that allow for faster, more predictable payouts. Here, insurance is not merely a safeguard for individuals but a strategic tool for governments, businesses, and infrastructure systems to reduce financial exposure and incentivize pre-disaster mitigation. The section also addresses the often-overlooked vulnerability of **public infrastructure**, calling for expanded insurance strategies at the state and municipal levels to protect assets and reduce post-disaster fiscal shocks.

Across these contributions, a consistent theme emerges, *financial resilience is a core capability of disaster resilience*, not an optional layer. Insurance is one of the few tools that can provide rapid liquidity, empower autonomous recovery, and reduce pressure on federal aid systems. But achieving broader and more equitable coverage requires more than subsidies or mandates, it demands behavioral insight, systemic reform, and innovation that aligns incentives across sectors.

Section 4 ultimately challenges readers to rethink the financial architecture of resilience. It calls for a *new paradigm of preparedness*—one that integrates behavioral science, market tools, and public policy to create a future in which individuals, communities, and institutions are not only structurally sound, but *financially secure* in the face of escalating flood risks.

Flood Risk Perceptions, Insurance Decisions, and Innovation

David J. Alexander, Ajmal Aziz, Llewellyn Salgado[48], Ji Sun Lee[49], and John Huffman[50]

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Abstract

There is a large flood insurance gap in the U.S. despite a steady increase in the number of flood disasters and financial losses. To understand this gap, DHS S&T pursued a series of flood insurance studies into public perceptions and insurance decisions for individuals and communities. This chapter summaries the findings of these research efforts to assist FEMA in meeting NFIP objectives to increase the number of flood insurance policies across the U.S. and reduce disaster suffering and economic losses from flooding. These studies were intended to provide FEMA new insights into public perceptions of flood risks, insurance decisions for homeowners, small businesses and communities, and potential scientific and technological advances that may benefit the NFIP and the flood risk management community in meeting these challenges.

Keywords

NFIP, flood insurance gap, public perception, customer segmentation, Likert scale

1. Introduction

"People shouldn't be living in certain places - on earthquake faults or on flood plains. But they do, and there are consequences. (Smil 2018)[51]

It is widely recognized that flooding is the most frequent and costliest disaster in the U.S. The financial magnitude of this state-of-affairs is even less recognized and understood by the public. Flood related disasters have cost the US more than $850

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[51] Quote from Vaclav Slim, Distinguished Professor Emeritus at the University of Manitoba. Sourced from Rex Burress (2018). When Water Rages. Sierra Club, September 20, 2018. Accessible at https://www.sierraclub.org/mother-lode/yahi/september-20-2018

billion in damages and losses since 2000, and these trends are not slowing down, exacerbated by unbridled economic development and climate change (Pew 2022). The longitudinal analysis of fiduciary data shows that those with flood insurance recover faster and suffer less financial hardship than those without flood insurance (Kousky and Wiley 2021). As the administrator of the National Flood Insurance Program (NFIP), the U.S., through FEMA, is the largest single peril insurance provider on the globe, underwriting more than $1.2 trillion in U.S. residential and small business assets (FEMA 2022). Not surprisingly, DHS and FEMA have vested interests in understanding these trends and the strategic drivers, new and emerging risk factors, and scientific and technological advances at play in the flood risk transfer sector. Additional facts on U.S. flood risk from FEMA are 99% of U.S. counties are impacted by some form of flooding, effecting all US states and territories. Through 2022, the average flood insurance policy premium was $700 per year. For that same 2022 year, the average flood insurance claim payout was $52,000. A homeowner with a 30-year mortgage residing in the 100-year high risk, special flood hazard area has a 26% chance of experiencing a flood over the term of that mortgage policy. Despite these statistics, flood risk is poorly understood by the U.S. public, resulting in widescale underinsurance. (FEMA 2022). DHS S&T sought to better understand this flood insurance gap, through a series of foundational research studies into public perceptions of flood risk and insurance decisions by individuals and communities. This chapter summarizes the results from these studies.

2. Flood Risk Perceptions in Northern Virginia

In 2018, DHS S&T funded researchers from the Wharton school that produced a seminal report on the emerging private flood insurance market (Cousky et al. 2018).[52] The result of this study generated additional questions regarding flood risk perception, customer segmentation and product design, and market innovation in addressing the growing flood protection gap across the U.S. Accordingly, DHS S&T embarked on a series of research projects intended to look deeper into these areas of flood risk management.

2.1 Flood Risk Perceptions: A Case Study in Northern, Va.

With the growing challenges of flood disasters and underinsurance across flood prone areas, S&T sought to examine local knowledge and perceptions of flood risk and to assess factors that are influencing their risk-based decision-making. This approach was intended to provide foundational knowledge to advance technology innovation and improve flood insurance provisioning. As an initial use case, the Research Triangle Institute (RTI) conducted a study that explored these research objectives in communities located in northern Virginia combined with analysis of demographic characteristics of the populations living in flood-prone or at-risk areas.

[52] Cousky, Carolyn, Howard Kunreuther, Brett Lingle, and Leonard Shabman. (2018). The "Emerging Private Residential Flood Insurance Market in the United States. Wharton Risk Management and Decision Processes Center, University of Pennsylvania. Research was funded through the United States Department of Homeland Security, Science and Technology Directorate under contract HSHQDC-17-C-B0032.

A sampling plan and survey instrument was developed along with outreach to community organizations in the targeted areas. The survey was conducted over several months from October 2017 through April 2018. Community organizations were asked to support the study and assist with the distribution of the surveys. Over 900 local and regional organizations, including municipal government agencies, religious and faith-based institutions, civic leagues and neighborhood associations, library systems, chambers of commerce and visitors' associations, and environmental and conservation groups were contacted. To enable a greater response rate and access to a diverse population, a multimodal approach was taken with options including using a paper questionnaire (distributed at meetings or community events, or by community leaders) or online (distributed via email or social media or posted on websites or forums (RTI 2018).

The survey was not intended to assess flood insurance market penetration in the targeted areas; however, the number of residents that reported having flood insurance provided insight into gaps that need to be addressed. The final statistics for the survey sample were 329 total responses with 316 completed and 13 partially completed. 37.4% of the surveys were completed in-person, while 61.4% were completed on-line. 61.4% completed the lone version and 31.6% completed the abbreviated version.

2.2 Core Research Questions and Findings

Nine core research questions were covered in the study and grouped into four types of queries: 1) questions of sample description, 2) questions that compare people based on ownership status or geography, 3) questions that involve prediction of insurance behavior as a function of various factors, and 4) questions that involve information source exposure and preferences. key findings are summarized for each of these questions as follows.

2.2.1 Questions of Describing the Survey Sample Population

RQ1. What are the demographic and geographic characteristics of property owners and residents in the survey sample, both overall and among those who live in flood zones?

There were more female than male respondents (58.0% vs. 42.0%). Age distribution among the overall sample ranged from 4.8% among the youngest cohort (aged 18–29) to 28.0% among the group aged 60-69. The other four age cohorts represented between 15.1 and 20.9% of the sample.

Most of the sample was White (83.8%) and non-Hispanic (97.4%). Among the four targeted geographic areas, most respondents lived in the Hampton Roads/Tidewater MSA (60.2%). Fairfax County represented 26.4% of all respondents. Respondents living in the Eastern Shore made up 8.9% of the sample, and the Richmond MSA represented 4.5% of the sample.

Most respondents said that they did not obtain flood insurance when they purchased or moved into their home (55.6%). More than one-third did purchase flood insurance (39.2%).

Most respondents did not currently have flood insurance (53.5%). Among those who live in a flood zone, 70.2% currently had flood insurance compared with 19.7% of respondents who do not live in a flood zone. Over two-thirds of those who reported living in a flood zone reported obtaining flood insurance when they purchased or moved into their home (67.2%) compared with 28.2% of those who do not live in a flood zone. Among those who did not report living in a flood zone, nearly one-fifth (18.9%) reported obtaining flood insurance when they purchased or moved into their home, whereas three-quarters (75.6) did not obtain flood insurance.

RQ2. Do business owners in flood zones in the survey sample tend to hold flood insurance for their businesses?

43 respondents, or 13% of the sample population, said that they were business owners. Among those, 44.2% reported that their businesses are not located in a flood zone. 81.4% of 43 respondents said that they do not possess flood insurance for their business. Among the 12 business owners who reported their business was in a flood zone, 3 indicated that the business location had flood insurance.

RQ3. What do property owners/residents in the survey sample tend to believe about flood insurance, the likelihood of flooding and flood damage, and policy?

Generally, respondents believed that 50.0% or fewer of the people living in flood zones have flood insurance (72.0%). Overall, most respondents disagreed that flood insurance is a topic that is generally easy to understand (55.2%). Nearly half disagreed that the benefits of flood insurance are easy to understand (49.9%), while 17.1% neither agreed nor disagreed. Nearly three-quarters of respondents agreed (agree or strongly agree) that they understand how to get flood insurance (73.8%). 57.4% indicated tropical storms or hurricanes as being the most likely cause of flooding in their area. 26.7% reported nor'easters as being the most likely cause of flooding (26.7%). 20.7% listed rainfall as the most likely cause of local flooding (20.7%).

More than one-third of respondents (36.8%) indicated that *real estate agents* are most responsible for warning residents that their property is located in a flood zone. One in five respondents said it is the buyer's or resident's own responsibility to know (20.1%). Nearly the same amount said it is the local government's responsibility to warn residents (18.2%). Just over half of respondents (51.1%) said that the *property owner* is responsible for protecting their property from flooding and flood damage. More than 9 in 10 respondents agreed that a *flood insurance company* should be responsible (91.4%). Approximately three-quarters of respondents agreed that a *homeowner's insurance company* should be responsible (75.2%). *Mortgage companies* were indicated as having responsibility by the fewest respondents. Only 10.8% agreed that mortgage companies should be responsible for repairing or replacing damaged property.

Most respondents said that flood damage would be less than 10% of the value of the home (56.0%), while 31.1% reported that there would be no damage if a flood occurred in their area. Over one-quarter of those who responded believed that total costs would be in the lowest range, $0 to $2,999 (27.3%). Most respondents (53.6%) reported believing that the total cost would be in a range less than $25,000. Only 9% of those who

responded believed that the total cost would be in a range greater than $250,000. 42.9% of those who responded believed that out-of-pocket costs would be at the lowest end of the scale, ranging between $0 and $2,999. Nearly three-quarters of respondents (72.0%) estimated out-of-pocket costs would be in the range less than $10,000. 92.4% said they would be less than $50,000. Only 1.5% of those who responded believed out-of-pocket costs would be in a range greater than $250,000.

The most frequently indicated reason for increases in costs was development in flood-prone areas (61.7%), followed by flooding that is more frequent (52.9%). Individuals' lack of planning (47.4%), communities' poor education efforts for residents (31.3%), and governments' lack of protection for properties (24.9%) were also indicated by respondents as influences on increasing financial damages and losses from flooding.

2.2.2 Questions that compare people based on ownership status or geography.

RQ4. Are there differences between non-owners and homeowners in terms of flood insurance possession, concern about living or owning property in a flood-prone zone, knowledge regarding the flood zone status of one's residence or owned property, reported ability to understand flood insurance, and beliefs about responsibility for flood protection and mitigation?

Among those who live in a flood zone, a higher percentage of owners compared with nonowners reported having flood insurance (46.4% vs. 9.3%; $p < .001$). When asked who should be responsible for repairing or replacing the property if damaged or destroyed by flooding, owners reported higher scores – indicating higher agreement with the idea that it was their personal responsibility, while nonowners reported higher scores – indicating higher agreement with the idea that it was a developer's/home builder's; a mortgage company's; or a local, state, or federal government's responsibility.

When considering costs associated with flood damage, there were no significant differences between owners and nonowners in the perceptions of *overall* or *out-of-pocket costs* for repairing or replacing properties damaged by flood. There were also no significant differences between owners' and nonowners' perception of who is responsible for warning buyers and residents that a property is in a flood zone or for protecting property in Virginia from flooding.

RQ5. Are there differences between residents living in the targeted areas of interest—communities in coastal areas (Hampton Roads/Tidewater and the Eastern Shore) and noncoastal areas (Fairfax County and Richmond)—in terms of flood insurance possession, concern about living or owning property in a flood-prone zone, knowledge regarding the flood zone status of one's residence or owned property, and reported ability to understand flood insurance?

A significantly higher percentage of respondents living in coastal areas reported living in a designated flood zone compared with those living in noncoastal areas (48.4% vs. 26.8%; $p < .001$). Among those who indicated they live in a designated flood zone, a significantly higher percentage of individuals living in coastal areas reported currently having flood insurance than those living in noncoastal areas (44.4% vs. 30.9%; $p = .024$).

Those living in coastal areas reported perceptions of lower overall costs associated with repairing or replacing homes damaged by flooding (MC = 3.9, SE = 0.2, MNC = 4.7, SE = .3, p = .038). Those living in coastal areas also reported perceptions of lower out-of-pocket costs for repairing or replacing the home if damaged by flooding than those living in noncoastal areas (MC = 2.3, SE = 0.2, MNC = 3.2, SE = 0.3, p = .001).

Those living in noncoastal areas reported higher scores – indicating higher agreement with the idea that it was their personal responsibility, while those living in coastal areas reported higher scores – indicating higher agreement with the idea that it was the local or federal government's responsibility. There are no significant differences between those living in coastal areas and those living in noncoastal areas in perceptions of responsibility for warning and protecting residents and properties.

RQ6. Are there differences between residents living in known flood zones versus those who do not in terms of flood insurance possession, concern about living (or owning property) in a flood-prone zone, knowledge regarding the flood zone status of one's residence or owned property, and reported ability to understand flood insurance?

A significantly higher percentage of respondents who reported living in designated flood zones indicated currently having flood insurance, compared to than those who reported not living in designated flood zones (70.2% vs. 19.7%; p < .001). Those living in flood zones have higher perceptions of overall cost to repair or replace the home if damage/destroyed by flooding than those not living in flood zones (MF = 4.6, SE = 0.2, MNF = 3.6, SE = 0.2; p = .001). There are no significant differences in perceived out-of-pocket costs between those living in a flood zone and those who do not. Those living in flood zones reported higher scores – indicating higher agreement with the idea that it was a flood insurance company's responsibility to repair or replace a property damaged by flooding, while those not living in flood zones reported higher scores – indicating higher agreement with the idea that it was a developer's or home builder's responsibility.

2.2.3 Questions that involve prediction of insurance behavior as a function of various factors.

RQ7. Do past experiences, demographic or geographic factors, or knowledge or beliefs about flood insurance predict flood insurance possession?

Those who own their property were almost 10 times more likely to have purchased flood insurance at the time of purchase or occupancy than nonowners (OR = 9.71, 95% CI = 2.19–42.95; p < .001). Those who reported residing in a flood zone were five times more likely to have had flood insurance when their property was purchased or occupied compared with those not living in designated flood zones (OR = 5.08, 95% CI = 2.26-11.41; p < .001). Those with higher perceptions that people around them have flood insurance (e.g., thinking that about 75% of people had flood insurance compared with thinking that 50% of people had flood insurance) were almost twice as likely to have purchased flood insurance at the time of purchase or occupancy (OR = 1.79, 95% CI = 1.29-2.47; p < .001). Those with higher perceptions of overall cost to repair or replace the property that was damaged because of flooding are 1.5 times more likely than those

with lower perceptions to have purchased flood insurance at the time of purchase or occupancy (OR = 1.51, 95% CI = 1.15-1.97; p = .003). Those who own residential property were 21 times more likely to currently have flood insurance compared with those who do not own their property (OR = 22.01, 95% CI = 3.86–114.42; p < .001). Those who reported living in a flood zone were more than 11 times more likely than those not living in a flood zone to have current flood insurance (OR = 11.52, 95% CI = 4.47-29.69; p < .001).

Those with higher perceptions that people around them have flood insurance were 1.6 times more likely than those with lower perceptions to have current flood insurance themselves (OR = 1.65, 95% CI = 1.16-2.35; p = .006). Those with higher perceptions of the overall cost to repair or replace the property that was damaged because of flooding were almost 1.8 times more likely than those with lower perceptions to have current flood insurance themselves (OR = 1.77, 95% CI = 1.31-2.39; p < .001).

Flood insurance coverage was also related to perceived knowledge of how to obtain flood insurance. Those with higher perceived knowledge of how to get flood insurance are twice as likely to have current flood insurance (OR = 1.89, 95% CI = 1.21-2.95; p = .005).

2.2.4 Questions that involve information source exposure and preferences.

RQ8. Where do residents get information about floods including alerts, warnings, and notification, what actions would they take in response to a flood warning and what information sources may affect their decision to purchase flood insurance?

Television was the most frequently indicated (78.7%), followed by radio (64.4%) and cell phone alerts (63.2%). Only 5.8% of respondents said that they do not receive any flood risk advisories or warnings. In response to a flood warning, more than one-third (35.3%) said that they would seek more information through broadcast media news sources (TV and radio), and a quarter (25.2%) reported that they would go online to get more information.

Approximately one-quarter of respondents said that they would secure their home or belongings (23.4%) in response to a flood warning. Fewer than 1 in 10 respondents said they would move to a higher floor in the home (6.1%), ignore the warning (5.8%), or contact the police (3.6%) or friends and family (2.7%) in response to a flood warning.

Nearly two-thirds of respondents indicated banks or mortgage companies as a source that might affect their insurance purchase decisions (63.5%), making it the most frequently selected source. Insurance companies (52.0%), local government officials (48.6%), and real estate agents (48.3%) were also indicated by a near majority of respondents as influential sources.

Weather experts (31.9%), local media (31.0%), and state (30.7%) and federal (28.3%) government officials followed in terms of being reported as a likely influencer. Fewer than 1 in 10 respondents reported that social media (7.6%) would affect their flood insurance purchase decisions, and only 5.8% said that they could not be convinced to buy flood insurance at all.

RQ9. Are there differences in where residents get their flood information based on property ownership, geography, or residence in a flood zone, including how flood warnings are received, how to respond to a flood warning, and whether to purchase flood insurance?

A significantly higher percentage of nonowners compared with owners (O = 36.9%, NO = 53.7%; $p = .022$) and a significantly higher percentage of those living in coastal areas compared with those in noncoastal areas (C = 44.0%, NC = 29.9%; p = .018) said they receive flood advisories, watches, or warnings through *social media*. In addition, a significantly higher percentage of those living in coastal areas (C = 39.2%, NC = 26.8%; $p = .033$) reported that they receive this information through *friends and family*.

A significantly higher percentage of respondents living in noncoastal areas compared with those living in coastal areas (C = 18.1%, NC = 42.3%; p < .001) reported that they would go online to get more information. Very few respondents indicated that they would contact friends and family to see what they were going to do (n = 9) or contact the police or other emergency services to ask about the risk (n = 12).

When comparing across property ownership status, a significantly higher percentage of owners compared with nonowners indicated that local government officials (O = 51.8%, NO = 33.3%; p = .014), real estate agents (O = 51.5%, NO = 33.3%; p = .016), and bank or mortgage companies (O = 67.5%, NO = 42.6%; p = .001) might convince them to purchase flood insurance. A significantly higher percentage of nonowners than owners reported that social media posts (O = 5.1%, NO = 20.4%; p = .001) would convince them to purchase flood insurance. A significantly higher percentage of those living in noncoastal areas than in coastal areas reported that local government officials (C = 42.2%, NC = 63.9%; p < .001) and state government officials (C = 25.9%, NC = 42.3%; p = .004) could convince them to purchase flood insurance.

A significantly higher percentage of nonowners than owners said that they could not be convinced to purchase flood insurance (O = 4.4%, NO = 13.0%; p = .019).

2.3 Opportunities for addressing Flood Insurance public perception and decision challenges.

The results from this survey offer some compelling insights on flood risk perception from the local community and individual levels. The overall responses indicate that residents have a low awareness and knowledge of flood risk, how to plan for flood events, and the benefits of flood insurance; underestimate potential damages and costs associated with flooding; and misunderstand who is responsible for warning residents about flood risks, protecting properties against flood damage, and assuming costs for repairing or replacing damaged properties.

3. Flood Risk Perceptions and Insurance Decisions

3.1 Understanding Flood Risk Perceptions through customer segmentation and voice of the customer analysis

Building off the findings from the case study on flood perceptions in Northern

Virginia communities, S&T commissioned research to further understand flood risk perceptions using customer personas and segmentation analysis based on data from a qualitative survey of 960 residents living within the 100-year flood zones across the U.S.

Results from this expanded survey are comparable to the Northern Virginia case study and amplify the need for improved consumer education and risk communication but also an emphasis toward product innovation to better address the changing nature of flood risks and the various needs for financial protection against flooding. The survey results suggest that flood product innovation may offer an opportunity to drive flood insurance take-up rates through better alignment to individual personas of risk and desired outcomes of the NFIP in lowering flood risk. More specifically, analysis of the survey sample results show that 31% of residents in counties with 100-year flood zones have flood insurance, and that the top reasons for not having flood insurance in these counties are: (1) perception of not living in a high-risk flood zone, (2) the area has not flooded since the customer lived there, (3) the property does not have a basement, (4) does not live near a river, lake, stream, or ocean, (5) cost is too high, (6) and the insurance agent said it was not needed. These results directly equate to the survey respondents' perceptions of flood risk, which are consistent with the findings form the Northern Va. Case study.

The survey results yielded some useful insights for framing future research and technology or product innovation. Many of the respondents who have flood insurance are satisfied with their flood insurance products, at least compared to other types of insurance like auto and homeowners. The survey results indicate consumers do see the value of flood insurance when their risk perceptions change, and when the flood insurance product is suited to their individual needs. This suggests that improvements in flood risk education and communication coupled with flood insurance product innovation offer potential opportunities for expanding flood insurance coverage across the US; and thereby, lowering the flood protection gap.

4 Innovating in Flood Insurance

4.1 Understanding the Flood Insurance Purchase

One of the key areas identified for further study from the previous surveys was examining new approaches to better understanding the flood insurance consumer. How can we improve understanding and awareness of the customer and how they currently use not just purchase flood insurance products?

To address these research questions, we examined the issues using customer segmentation and consumer typing based on a typical purchase funnel (see Fig. 22). for flood insurance. A purchase funnel served as a guide to measure the biggest area of leakage for flood insurance. Market analysts would consider this as a means of assessing customer attitude and usage, and therefore, customer satisfaction. It also enabled us to breakdown the flood insurance market into discrete segments based on psychographic mindsets. Using this approach, it was possible to estimate three stages

of this purchase funnel: awareness, purchase, and loyalty (GFI 2022).[53] Key objectives and specific questions in the data collection plan are included at the end of this chapter.



Fig. 22: *Flood insurance purchase funnel (GFI 2022).*

Several key themes and findings emerged from analysis of the subject matter expert (SME) conversations conducted during the study (see Fig 23.) in tandem with the survey results analyzed by customer segments. The insurance industry was mainly focused on incremental operation advances, rather than more fundamental disruptive innovation. Many of the incremental advances used off-the-shelf technologies that were currently in use in other industries, especially banking and other financial services. These are viewed as quick wins, especially by those who are part of innovation labs or centers. The operational areas that are most affected are customer service and removing human touch points from the process to make the process easier, faster, more convenient and reduce labor costs for the insurance carriers. Many of these innovations relied on third party data to auto-populate forms, such as applications and claims and there was a nascent use of artificial intelligence using large language models in this regard.

[53] Growth Focused Insights and Research (GFI). (2022). Future of Flood Insurance Final Report. Research was funded through the United States Department of Homeland Security, Science and Technology Directorate under contract 70RSAT21CB000026.

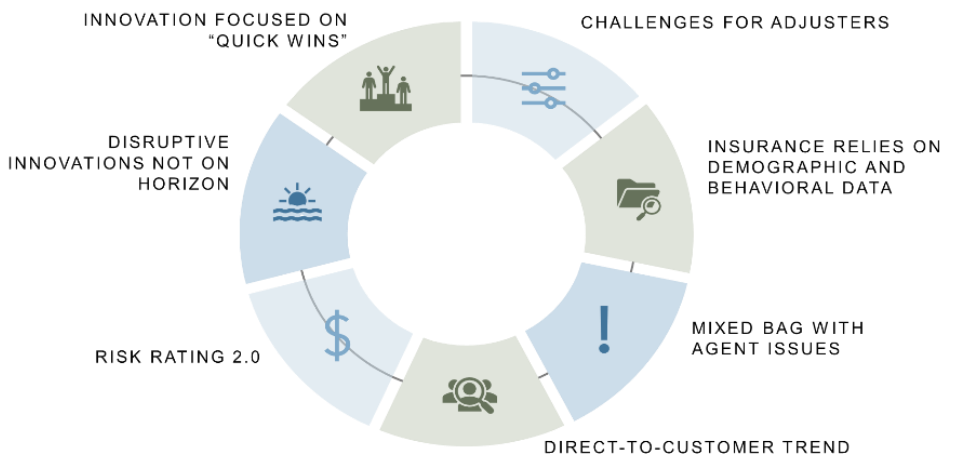


Fig. 23: *Key themes and findings from the SME conversations. (GFI 2022).*

The industry is also looking to improve the role of agent and adjuster in provisioning insurance policies. In that regard, near-term solutions were focused on making both writing policies and adjusting claims more efficient to lower operating costs (especially labor) without any negative effects on the volume of insurance purchases and adjustments. Doing more with less.

Industry continuity was also an important factor, especially given the NFIP monopoly on flood insurance in the US. At the time of this study, FEMA had just announced and began launching NFIP Risk Rating 2.0. Issues with FEMA implementation of Risk rating 2.0 clearly showed up in the interviews and questionnaire results, particularly with realtors and mortgage brokers. While one might consider this ancillary, it directly impacts the flood insurance market based on NFIP's flood insurance monology. Issues related to those purchasing new flood insurance policies and those renewing existing flood insurance policies. Realtors were reporting that homeowners are receiving flood insurance rates that are five or six times higher than the previous policy on the same property. Mortgages lenders reported confusion over the mandatory purchase requirement versus voluntary purchase. These concerns are endemic to flood insurance perceptions issues, regardless of whether specific cases are actual or perceived. Why, because both realtors and mortgage lenders believe them.

The results from the consumer perspective were more intriguing. Five major mindsets emerged giving some indication of what drives the purchase of flood insurance (see Fig 24). Some of these are not surprising, such as price matters, but others are more revealing, such as the importance of customer service and the need for peace of mind. As expected, the concept of 100-year flood zone came into play across these mindsets as the concept is easily misinterpreted as happening once every hundred years.



Fig. 24: *Five flood insurance consumer mindsets. (GFI 2022).*

The need vs legal requirement mindset introduces a dichotomy between those who have insurance only because it is a legal requirement and those who have it because it's a good idea. Cost-benefit analysis mindset indicates many flood insurance consumers are very prudent and consider the tradeoffs through some kind of mental calculus (whether ill-informed or not) before purchasing insurance. These consumers consider factors such as their ability to make repairs, the probability of flooding, the cost to pay-off a mortgage to avoid the legal requirement and the cost of insurance over the long term. Compare that with more price conscious consumers that simply look at the cost, and if this is something they can afford. If the answer is no, they just assume the risk and take a chance of not experiencing a flood. What is promising is that many consumers purchase insurance, not just flood insurance, simply to have a "peace of mind." These consumers placed more value on reducing risk and on preserving their property than on short-term financial considerations.

4.2 Influence Opportunities in Flood Insurance Marketing

Examining these survey results (960 completed surveys) through the lens of flood insurance marketing provided a basis for identifying influence opportunities for improving flood insurance marketing that might generate more insurance uptake. This analysis was done using a Likert Scale. A Likert scale is a unidimensional scale used for determining respondents' attitudes and opinions such as the degree to which someone agrees or disagrees with a concept or is satisfied or unsatisfied with a product. A Likert scale is typically designed using multiple points, ranging from a 5-point to an 11-point scale. For this study, GFI employed a 6-point scale to take advantage of the unique

property of multiples of six and to reduce the number of points on the scale to accommodate those who took the survey on mobile devices. The unique property of a six (or twelve) point scale is that they can either be used as a high, medium, or low measure, or as a high/low measure. The high, medium, low measure, such as Agree, Neither Agree/Disagree or Disagree is created by combing the top two points on the scale (also known as "Top 2 Box" or T2B), the middle two points and the bottom two points (also known as "Bottom 2 Box" or B2B), and then computing a percentage for each. The low/high measure, such as Agree/Disagree is created by combining the top three boxes to create the "Top 3 Box" (T3B) and the bottom three boxes to create the "Bottom 3 Box" (B3B), and then creating a percentage. While there are times when it might be slightly better to use a mean score (such as displaying the importance/performance scores on one graph), since the Likert scale is an ordinal scale, for consistency this analysis used a percentage T2B or T3B.

The product of the Likert scale was a four-segment scheme, referred to as personas that optimized resources, especially time, and data efficiency, and offered a nice discrimination between segments based on the defining characterization (see Fig. 25). The defining characteristics are those attributes, in the context of flood insurance, where a segment scored either 10% above or below the average and offered a useful insight into the personality of the persona. The use of 10% was reasonable given the limited number of segments and small sample of 960 completed surveys, which was a known limitation of this study. The four personas are described as Optimistic Influencer, Trusting Risk Taker, Satisfied Loyal Optimist, and Risk Averse Pessimist. The attributes in the table represent those that are relevant and that are +/- 10% from the average measure for that attribute.

Optimistic Influencer	Trusting Risk Taker	Satisfied Loyal Optimist	Risk Averse Pessimist
26% of consumers	21% of consumers	15% of consumers	37% of consumers
37% have flood insurance	22% have flood insurance	52% have flood insurance	22% have flood insurance
Condo/Apartment	Owns Home	Single Family Home	Condo/Apartment
Lives in 100 yr Flood Zone	Has Mortgage	Own home	Rent
Have Flood Insurance	Trusts Federal Government	No Mortgage	Doesn't have Flood Insurance
Satisfied with NFIP	Quick Decider	Have experienced flood	Not Satisfied with any type of insurance
Doesn't Trust FEMA	Assumes Risk for Long-term Payoff	Lives in 100 yr Zone	Lives Near Flood Zone
Doesn't Trust DHS	Not experienced flood	Have Flood Insurance	Reasonable
Optimist	Not live in Flood Zone	Satisfied with Flood Ins	Factual
Social Group Leader	Flood Insurance Not Important	Have Flood Insurance	Quick Decider
	Flood Agent Reco. is important	Satisfied with Flood Ins	
		Customer Service Important	
		Satisfied with NFIP	
		Real Estate is Good Investment	
		Trusts Federal Government	
		Loyal	

Fig. 25: *Four segmentation personas. (GFI 2022).*

Optimistic Influencer: This type of consumer represents 26% of the market and 37% have flood insurance, which is 20% above the average. These consumers tend to have flood insurance and are satisfied with the NFIP, but do not trust FEMA or DHS. Interestingly, these consumers are optimistic and are social group leaders.

Trusting Risk Taker: This type of consumer is much less likely to have flood insurance and constitutes 21% of the market. These people own a home and have a mortgage. They do not think they live in a flood zone and are less likely to have experienced a flood. These consumers trust the federal government, are quick deciders.

Satisfied Loyal Optimist: This is the segment most likely to have flood insurance. Over 50% have flood insurance, are more likely to be satisfied with it and with the NFIP, to live in a 100-year flood zone, trusts the federal government and are loyal. They are also less likely to have a mortgage. However, they only represent 15% of the market and are the smallest segment.

Risk Averse Pessimist: This is the largest segment, constituting 37% of the market, and only 22% have flood insurance. This segment is not satisfied with any type of insurance, more likely to rent an apartment or condo, and lives near a flood zone. These consumers are quick deciders and rely on facts to make decisions.

When developing flood insurance marketing and communication strategies, these results suggest that all four of the personas should be factored into outreach campaigns. Such an approach could help increase the success of a particular product or message across all customer types and reduce the risk of making a problem worse. For example, the Optimistic Influencer and Risk Averse Pessimist do not trust FEMA or DHS. Thus, a message that is branded as FEMA or DHS might have the opposite effect and raise skepticism over the believability of the intended messages. Conversely, the best opportunities for influence would be the Trusting Risk Takers and the Risk Averse Pessimists, which constitute 21% and 37% of all consumers, yet only 22% have flood insurance.

4.3 Barriers to Purchasing Flood Insurance

Let's reconsider the flood insurance purchase funnel mentioned earlier. Analysis of survey results applying the flood insurance purchase funnel shows 76% of those who live in a county with a 100-year flood zone have awareness of flood insurance policies and are familiar with them. Only 31% of consumers currently have a flood insurance policy. The good news is that 84% of those who have a flood insurance policy report being satisfied. These results indicate that the best opportunity to influence flood insurance uptake is at the point of purchase. This means we need to better understand any barriers to purchasing flood insurance and what drives that purchasing decision to identify potential options for what can be done to overcome these issues (i.e.; offering incentives). Deeper analysis of the survey results provides some insight into these questions. As a follow-up question, the survey asked respondents who did not have flood insurance the reasons for not having flood insurance. This was a multi-select

question, so respondents were able to provide multiple reasons for not having insurance. Results are shown in figure 26.

Each of these reasons is a different way to measure flood risk perception or misperception. For example, the top four reasons given for not having flood insurance relate to the false sense of security stemming from the in-out nature of the special flood-hazard area (100-year flood zone) or apathy due to not having experienced a flood disaster. 43% of respondents who live in a county with a 100-year flood zone gave the reason for not having flood insurance because they believe they do not live in a high-risk flood zone. 33% of respondents gave as a reason that there has not been flooding in the area since they lived there. 26% of respondents do not have a basement at risk of flooding. 24% of respondents do not live near a body of water (rivers, streams, lakes or ocean). In other words, these respondents do not believe that they have a high risk of flooding.

Which of the following, if any, help explain why you do not currently have a flood insurance policy?	
Reason	**Percent Selected**
Do not live in a high-risk flood zone	**43%**
There has not been any flooding in my area since I lived here	**33%**
Do not have basement	**26%**
No nearby rivers, streams, lakes or ocean	**24%**
Cost is too high	**23%**
Insurance agent said it was not needed	**15%**
Coverage is not worth the cost	**14%**
Mortgage company does not require	**13%**
Do not know how it works	**11%**
My neighbors don't have flood insurance	**10%**
Deductible too high	**10%**
Do not know anyone who has flood insurance	**8%**
Other (Please Specify:)	**8%**
Would not know where to get it	**7%**
Have other precautions such as having a sump pump or drainage ditch	**7%**
Community leaders said it was not needed	**6%**
Don't like dealing with insurance companies	**6%**
Have enough funds to pay out of pocket if ever needed	**6%**
Homeowners Association will cover flood damage	**6%**
Difficult to get a quote	**5%**
FEMA/government would pay for flood damage without me needing insurance	**5%**
Can't find a provider	**4%**
Have a dry well	**4%**

Fig. 26: *Barriers to flood insurance purchasing. (GFI 2022).*

What these results show is that customer segmentation analysis offers a promising approach that provides meaningful insights to actively inform FEMA efforts to improve flood insurance marketing campaigns, consumer education, and eliminating purchasing barriers to flood insurance. Psychographic or attitudinal characteristics derived from customer segmentation analysis are not used much by the insurance industry or by other types of financial services firms. Financial services, including insurance, are more reliant on statisticians, data scientists, and actuarial science rather than those trained in social science or market research. Behavioral data is readily available internally, but there is a need for more data; they tend to go outside the organization to purchase other types of behavioral data to augment their existing data sets. This suggests an inherent bias against longitudinal data gathered from surveys and qualitative methods exists at insurance and financial services firms that precludes the adoption of robust customer segmentation analysis strategies.

Moreover, since insurance and financial services firms do not readily use this type of data, including DHS and FEMA, these entities can be blind to consumer problems or pain points like those highlighted in the flood insurance survey results, and less able to respond to them. Effective segmentation combines psychographic and attitudinal data with behavioral data to create personas. These types of data go beyond knowing what consumers are doing or feeling, but to why they do it or feel that way. Psychographic and attitudinal data analysis through customer segmentation often serves as the basis for creating an innovation pipeline (GFI 2022).[54]

4.4 Opportunities for Flood Insurance Technology Innovation

An area of particular interest for our studies was identifying opportunities for driving innovation in flood insurance, whether through changes in culture or technological development. Several of the research questions explored in our surveys and interviews provided some key insights into both emerging trends in the property and casualty insurance lines of business, latest developments in the Insurtech markets, or ideas shared during the SME interviews, including those from DHS S&T, FEMA and NFIP experts. One of the most common reframes captured in the SME interviews was that innovation must become a cultural mindset for the flood management and insurance community. Innovation must be recognized as a continuous process and that understanding customer needs aligned to national priorities for flood risk reduction is critical toward developing impactful innovations that solve industry or customer problems. It's not about technology; it's about solving a problem and removing barriers to insurance uptake (ie: closing gaps in the flood

[54] Growth Focused Insights and Research (GFI). (2022). Future of Flood Insurance Final Report. Research was funded through the United States Department of Homeland Security, Science and Technology Directorate under contract 70RSAT21CB000026.

insurance purchase funnel) (GFI 2022).[55]

Emerging InsurTech solutions are challenging the conventions of flood insurance underwriting, risk assessment, and claims processing. One promising avenue is the integration of artificial intelligence (AI) and machine learning (ML) to support pre-disaster underwriting, post-event damage assessments, and real-time customer service interactions. These technologies allow for rapid triage following flood events, potentially replacing or supplementing human adjusters with automated damage classification tools using aerial imagery, remote sensing, and structure-specific vulnerability models.

Beyond AI, other digital innovations include sensor networks and Internet of Things (IoT)-based systems that offer property-level flood detection and early warning. These can inform dynamic risk-based pricing models that reward households and businesses for deploying flood-resistant building materials or alert systems. DHS S&T's Flood Apex program highlighted that relatively low-cost sensors could be deployed at scale to increase situational awareness and provide input to predictive analytics platforms for community-level flood forecasting (Alexander et al., 2022).

Blockchain and smart contracts—although still nascent in flood insurance—may offer promise for parametric insurance products, streamlining policy activation, claims verification, and payout processes. Unlike traditional indemnity insurance, these mechanisms could automatically trigger payments when predefined flood parameters (e.g., water height or rainfall intensity) are met, reducing administrative burdens and delays. Several SMEs interviewed noted that, while the NFIP remains structurally constrained from offering parametric insurance under its current statutory authority, private-sector actors are already testing such approaches in commercial markets and international disaster contexts.

To catalyze these innovations, NFIP leadership and FEMA's Federal Insurance Directorate (FID) must act as conveners and enablers—partnering with the private sector, incentivizing pilot projects, and supporting a sustained culture of experimentation. As recommended in the DHS-funded research, appointing an internal Innovation Champion, creating an external Innovation Guide role, and launching a cross-functional innovation team are all vital steps toward institutionalizing a research-to-deployment pathway (GFI, 2022).

5. Conclusions, Study Limitations, and Recommendations

The flood insurance ecosystem is on the cusp of profound disruption. Three forces, in particular, are poised to reshape the landscape: direct-to-consumer delivery models, non-traditional market entrants, and rapid technological replacement of human adjusters.

The first disruption—direct-to-consumer models—challenges the traditional

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reliance on insurance agents. Just as retail, banking, and travel industries have shifted to online platforms that prioritize simplicity and speed, flood insurance could see similar transformations. Emerging players are already bypassing agents and going directly to consumers through app-based platforms and digital quote engines, many of which are designed with behavioral insights to improve user experience and increase uptake. This model lowers acquisition costs, accelerates enrollment, and aligns with consumer expectations of streamlined digital transactions.

The second major shift involves market entry from tech giants and non-traditional firms—Amazon, Walmart, Capital One, and Meta—whose core business models are not constrained by legacy systems or agent-based structures. These companies have demonstrated capacity to scale rapidly, experiment iteratively, and disrupt conventional sectors through user data analytics, digital infrastructure, and trusted consumer relationships. Should these firms enter the flood insurance space, they may cherry-pick the most profitable policies, destabilize incumbent portfolios, and erode market share for traditional insurers, including the NFIP.

A third and perhaps more immediate disruption centers on the replacement of human adjusters with automated claims technologies. While not without challenges, technology exists today to use drones, satellite imagery, and algorithmic models to estimate losses with precision. In the aftermath of a catastrophic event like Katrina or Sandy, the sheer scale of claims could accelerate the push for automation before legal, ethical, or procedural frameworks are fully mature. This would mark a significant shift in both labor and trust, potentially changing the nature of flood recovery interactions between the insurer and the insured.

Despite these promising trajectories, several limitations persist. Technological innovation alone cannot overcome deep-rooted public skepticism, lack of awareness, and policy constraints. As shown in the BESSE study in Virginia, residents routinely underestimate their personal flood risk, misunderstand who is responsible for damage mitigation and recovery, and lack clear knowledge about insurance options (RTI, 2018). Many do not perceive a need for insurance because they have not experienced flooding in their lifetimes, live outside formally mapped floodplains, or assume coverage exists under homeowners' policies. These behavioral barriers are not easily solved through better technology alone.

To bridge this gap, we offer the following recommendations:

1. Support continuous market research: FEMA and NFIP should institutionalize a longitudinal consumer insights program that uses psychographic segmentation, satisfaction trackers, and rapid-response feedback tools to shape innovation priorities.
2. Facilitate private-public collaboration: FEMA should establish an innovation consortium involving federal, state, academic, and private-sector actors to pilot test new insurance delivery models and parametric products.
3. Modernize NFIP statutes: Congressional reform is needed to allow NFIP to experiment with parametric and technology-enhanced insurance products,

broaden eligibility for incentive-based pricing, and integrate third-party data platforms.
4. Invest in education and trusted messengers: Partnerships with local agents, lenders, realtors, and community organizations are essential to increase flood risk literacy and influence purchasing behaviors, especially in low-penetration zones.
5. Institutionalize innovation culture: FEMA's Federal Insurance Directorate should adopt a permanent internal innovation unit, guided by an Innovation Champion and supported by flexible research and contracting mechanisms.

6. Key Themes, Questions, and Additional Readings

6.1 Key themes

- Innovation is cultural, not just technical: Solving the flood insurance gap requires embedding a mindset of innovation within FEMA, NFIP, and their partners—not just adopting new tools.
- Perceptions drive behavior: Misconceptions about flood risk, insurance affordability, and claims processes remain key barriers to closing the insurance gap.
- Disruption is inevitable: Direct-to-consumer platforms, automation, and new entrants from the technology sector are poised to fundamentally reshape the insurance market landscape.
- Behavioral insights matter: Research grounded in psychographics and user behavior—rather than purely demographic models—offers a clearer path toward higher policy uptake.
- Technology must serve trust and equity: Innovations must be designed with transparency, user-centricity, and accessibility in mind, especially for underserved populations.

6.2 Key Questions

As the flood insurance landscape continues to evolve, several critical questions emerge that should guide future research, policy reform, and innovation strategy. These questions are foundational to building a more inclusive, responsive, and resilient system of financial preparedness in the face of growing flood risk:

1. How can FEMA and the NFIP better align their innovation strategies with consumer behavior and perceptions of risk? Despite evidence of increasing hazard exposure due to climate change and urban development, many homeowners remain unaware of their vulnerability or believe that government aid will suffice in the event of disaster. How can behavioral insights be operationalized to recalibrate this perception and drive insurance uptake?
2. What role should the federal government play in incentivizing or de-risking private sector innovation in flood insurance? Given that the private sector remains hesitant to expand into the flood insurance space—largely due to NFIP

subsidization and regulatory uncertainty—what models of partnership, reinsurance, or public-private pilot programs could help bridge this divide?

3. What are the implications of agent bypassing and automation on equity, access, and trust in flood insurance markets? While direct-to-consumer platforms may streamline access and reduce costs, they also risk leaving behind populations with limited digital literacy, language barriers, or mistrust of institutions. What safeguards or standards should be implemented to ensure equitable innovation?
4. How can parametric and microinsurance products be introduced into the U.S. flood insurance system without undermining consumer protections? Parametric insurance holds promise for streamlining payouts and simplifying coverage options, especially for low-income households. But what regulatory, educational, and actuarial frameworks are needed to prevent misuse, misunderstanding, or adverse selection?
5. What is the most effective way to measure the success of flood insurance reforms and innovations? Traditional metrics such as policy counts or claims processed may not adequately capture the broader societal benefits of improved financial resilience. Should FEMA adopt new performance indicators related to household solvency, community recovery time, or mitigation investments?
6. What role should trusted intermediaries, such as lenders, realtors, and community organizations, play in promoting flood insurance literacy and uptake? Research suggests that residents often turn to these actors when making insurance decisions. How can their influence be better integrated into FEMA's outreach, training, and policy design?
7. To what extent should NFIP's mission evolve from a policy administrator to a market facilitator or innovation enabler? If the future of flood insurance requires greater private sector engagement, should the NFIP reorient itself toward standard-setting, market catalyzation, and product innovation, rather than direct service delivery?

These questions represent strategic inflection points for policymakers, practitioners, and researchers. They challenge longstanding assumptions about how flood risk is assessed, who is responsible for managing that risk, and what tools or innovations are most effective in building financial resilience. As climate risks accelerate and consumer expectations shift, answering these questions will be vital to crafting a future-ready flood insurance system.

7. Data Collection, Objective and Research Questions[56]

The four (4) broad objectives for the flood innovation study from GFI encapsulated the following objectives and research questions:

[56] Growth Focused Insights and Research (GFI). (2022). Future of Flood Insurance Final Report. Research was funded through the United States Department of Homeland Security, Science and Technology Directorate under contract 70RSAT21CB000026.

- Measuring the performance of flood insurance
    - Customer satisfaction
    - Compared to other insurance types
- Creating a culture of innovation
- Insights to "close the insurance gap"
- Innovations from the private sector

The eighteen (18) research questions were framing the data collection and analysis:

1. What efficiencies have been gained in terms of customer acquisition, claims processing time, and costs? Has this increased customer satisfaction?
2. What is the future of agent and adjuster compensation in an increasingly digital world?
3. How is compensation linked with customer satisfaction?
4. Are there tools and technologies that are being developed that would allow the NFIP to automate more of the adjustment process for certain claims?
5. Specifically, how are AI/ML or other techniques used in other Property and Casualty (P&C) lines? How is innovation stimulating new insurance line offerings? And how could the NFIP learn from these offerings in developing the flood insurance of the future?
6. What new products and offerings are insurers proposing based on new innovations?
7. How are insurance providers factoring purchasing behavior into their creation of new products? Are there emerging models of customer reactions to price increases that are influencing the way insurance is priced in the private market?
8. How are insurers helping to close coverage gap (required or otherwise) for populations unable to pay for full coverage? Are they exploring new offering types (like parametric) or very basic coverages?
9. How satisfied are customers with current flood insurance products and services?
10. How well do current flood insurance products and services perform?
11. What is the awareness level that the Federal Government backs flood insurance offerings through FEMA or NFIP?
12. What are short-term and long-term innovations NFIP should pursue to improve products and services?
13. Is there a product/services roadmap that can help NFIP create or improve products and services?
14. How should NFIP, FEMA or S&T measure success of these improvements?
15. Is there a mechanism to insuring that NFIP, FEMA or S&T can stay current with trends and innovations in the insurance industry or other industries that can be adapted to improve flood insurance products and services?

16. How does satisfaction and performance of NFIP products and services compare to private sector insurance products and services?
17. (Added November 2021) How have insurance companies segmented their business?
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The National Flood Insurance Program: Exploring Policy Concerns

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Abstract

Flood insurance is a necessary component of household and community resilience, providing reliable financial assistance to cover the costs of repairs and rebuilding without the need to draw down savings, divert consumption, or take on debt. Insurance provides greater and timelier assistance than federal disaster aid, which may take months or years to reach victims, reducing disaster suffering and disruption. The research effort examined the current state of flood insurance across the United States to address policy concerns with the National Flood Insurance Program (NFIP) and understanding of the flood insurance gap. The NFIP, administered by FEMA, has been providing flood insurance to households and businesses of participating communities for almost 50 years. Communities that join the NFIP must adopt minimum land use and building code regulations (defined by the program) in the FEMA-mapped 100-year floodplain, which is the area subject to a 1 percent or greater annual chance of being inundated by flood water, more commonly referred to as the Special Flood Hazard Area (SFHA). In 1973, Congress adopted what is known as the mandatory purchase requirement. This is a requirement that lenders require flood insurance for borrowers in the SFHA for loans that are federally backed or regulated. Despite this, there remains a large flood insurance gap in the United States; many at risk households do not have flood coverage. To help fill this knowledge gap and inform proposed policy and regulatory changes to the NFIP, a multi-phase research effort was undertaken to state of the emerging, private flood insurance market around the country, conduct a deeper exploration of flood insurance demand, with a detailed look at the mandatory purchase requirement and purchase of flood insurance outside the FEMA-mapped 100-year floodplain, and facilitating a hosted workshop to explore policy options for closing the flood insurance gap beyond a reliance on private sector offerings.

Keywords

Insurance, special flood hazard area, mandatory purchase requirement

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1. Introduction

"A flood insurance program is a tool that should be used expertly or not at all. Correctly applied, it could promote wise use of flood plains. Incorrectly applied, it could exacerbate the whole problem of flood losses." (White 1966)[59]

Flood insurance is a necessary component of household and community resilience. Flood events can impose enormous costs on households: repairs to their home, the need to replace damaged contents, as well as the costs associated with debris clean-up, evacuation, or temporary lodging if the flood made a home uninhabitable. Flood insurance provides reliable financial assistance to cover the costs of repair and rebuilding without the need to draw down savings, divert consumption, or take on debt. Insurance provides greater and timelier assistance than federal disaster aid, which may take months or years to reach victims, and the aid may be poorly matched to needs.

The National Flood Insurance Program (NFIP), housed in the Federal Emergency Management Agency (FEMA), has been providing flood insurance to households and businesses of participating communities for almost 50 years. It was created in 1968 as a voluntary partnership with local communities. Communities that join the NFIP must adopt minimum land use and building code regulations (defined by the program) in the FEMA-mapped 100-year floodplain, which is the area subject to a 1 percent or greater annual chance of being inundated by flood water. FEMA refers to this as the Special Flood Hazard Area (SFHA). Community residents are then eligible to purchase flood insurance policies through the NFIP. NFIP premiums at the time of our study were based on broad flood zones and certain aspects of a structure. As we return to at the end of the chapter, however, since our project, the program has modernized their approach to rate-setting. The basic structure of the program, however, has been largely maintained over the decades.

In 1973, early in the program's history, Congress became concerned that most communities were not participating in the NFIP and that when they did, few property owners purchased coverage. In response, Congress adopted what is known as the mandatory purchase requirement. This is a requirement that lenders require flood insurance for borrowers in the SFHA for loans that are federally backed or regulated. Despite this, there remains a large flood insurance gap in the United States; many at risk households do not have flood coverage. At the time of this project, many policy proposals were being explored to help close this gap, including encouraging growth in the small, private market for residential flood insurance, but there was very little understanding about the nature, extent, and possible expansion of this new market.

To help fill this knowledge gap and inform proposed policy and regulatory changes to the NFIP, we undertook a two-phase study beginning in the fall of 2017 and concluding in June of 2020. Phase 1 documented the state of the emerging, private flood insurance market around the country and Phase 2 undertook a deeper

[59] Gilbert White (1966). With the Task Force. *A Unified National Program for Managing Flood Losses.* House Document 465. Washington, DC: U.S. Government Printing Office.

exploration of flood insurance demand, with a detailed look at the mandatory purchase requirement and purchase of flood insurance outside the FEMA-mapped 100-year floodplain. (Kousky 2018). We also hosted a workshop on policy options for closing the flood insurance gap beyond a reliance on private sector offerings (Wharton 2018a)

2. Understanding the Private, Residential Flood Insurance Market

At the time we undertook this project, the private, residential market for flood insurance was just emerging. There was very little information, however, on the extent or nature of this new market or it its growth potential. Our project had two objectives:

1. document the state of the private flood insurance market across the country and the nature of coverage being offered, and
2. identify the main factors influencing the number and form of flood insurance policies offered by the private market.

In 2019, the National Association of Insurance Commissioners began collecting nationwide data on the private, residential flood insurance market. At the time of our study, however, no data was available. As such, the project team endeavored to identify every known private provider of flood insurance to build a systematic assessment of the size of the market and the types of policies being offered. We conducted semi-structured interviews with as many firms as were available and asked not just about their specific offerings but also their underwriting approaches. We also conducted interviews with a range of other stakeholders, including insurance industry associations and groups, state insurance regulators, realtors, FEMA staff, lenders, other policymakers, and additional individuals as appropriate. In addition, the project team also analyzed all pertinent legislation, regulation, and policies that had been adopted by both the federal government and states with respect to the private flood insurance market.

At the start of the project, Congress and FEMA were considering specific policy and regulatory interventions in the market and we sought to inform those proposals. In addition to characterizing the market, we explicitly explored market factors that we identified, though interviews and literature analysis, as potentially having a substantial bearing on the extent of private flood insurance offerings. These included the role of flood maps, data, and models for pricing flood insurance; mandatory requirements for purchase of flood insurance; the availability and costs of private reinsurance and other forms of risk transfer; current NFIP policies, procedures, pricing, and product offerings; and concerns about demand and supply of coverage (such as affordability concerns or protection against catastrophic losses).

2.1 Structure of the Private Market

Our survey of private providers of flood insurance resulted in an estimate that in 2018, private residential flood was roughly 3.5% - 4.5% of the total residential market, with the share growing. The market began with carriers offering policies in excess of the NFIP's $250,000 residential coverage cap and then expanded into the offering of

full stand-alone flood policies. Some of these policies mimic the NFIP terms and others offer more broader or more varied coverage. (Wharton 2018b)

In the United States, insurance is regulated by states. There are two broad classes of firms: admitted firms and surplus lines firms. Admitted carriers are licensed by the states in which they operate and their prices and policy terms must be approved by the regulator. In the case of insolvency, their claims are

backed by state guaranty funds. Surplus lines carriers, while facing some solvency and market conduct conditions, do not have their rates or forms regulated and are also not backed by state guaranty funds. Rate and form freedom allows them to specialize in difficult, complex, or catastrophic risks. The private flood insurance market largely began among surplus lines firms, but now there are also many admitted carriers offering flood coverage. States prefer agents to try and place insurance first in the admitted market and thus often require that policies can only be placed with a surplus firm when it has first been denied by several admitted carriers. At the time of our project, however, 19 states had waived such restrictions to foster a greater private market for residential flood coverage.

The nascent residential flood market was heavily backed by reinsurance, or insurance for the insurance companies. Reinsurance can help diversity catastrophic risks globally, increasing capacity. At the time of the project, we found that in many cases, reinsurers were taking a very large share of the risk, often in excess of 90%. Many market observers estimated that share would decline as primary insurers began to be more comfortable with writing flood policies. We also saw reinsurance companies driving the market by offering products that they fully designed, developed, and priced.

We documented three main types of flood policies being offered. The first we refer to as "NFIP+". These are typically offered in the FEMA 100-year floodplain, but with higher limits or broader coverage than NFIP policies. (Kousky 2018) These policies may try to match the terms of homeowners' policies and offer coverage on a replacement cost value rather than actual cash value basis, or at least provide the option to do so, as well as offer coverage for additional living expenses. The second type is a lower coverage policy issued as an endorsement outside high flood risk areas. These policies are targeted at properties with low risk of a catastrophic flooding. And the third type of policy was a complete mimicking of the NFIP policy terms. Firms varied, however, in the areas where they identified a profit potential or ability to compete against the NFIP. Some firms were only writing policies outside the SFHA, some were avoiding coastlines, and others were explicitly targeting high-risk, coastal areas.

Whereas the NFIP is required to take all customers in participating communities, regardless of the risk level, private insurers are selective in their underwriting. All stakeholders we interviewed agreed that the private sector will never be able to write policies for certain properties or locations. This almost universally included homes with a prior flood loss, for example; these properties have been costly to the NFIP, but the NFIP must keep insuring them. Many firms also agreed that certain geographic regions were "uninsurable." These tended to be coastal areas with a high density and subject to hurricanes, but also a couple hotspots of inland flood risk, such as around

Sacramento, California. All stakeholders agreed that these are properties and regions that instead need substantial investment in risk reeducation and climate adaptation.

2.2 Drivers of the Market

Large homeowners insurance companies have been reluctant to enter the flood market since flooding is a catastrophic peril and the NFIP exists and can insure that risk. They are concerned about the concentration of risk in their portfolio and possible correlation with exiting wind policies in coastal regions. They may also be concerned about price fluctuations in the reinsurance market. Finally, we heard in interviews there is also reluctance to begin to offer flood coverage when insurers feel it could be difficult, either because of regulatory pressure or consumer upset, to adjust prices and terms over time as they learn more about the risk (Bradt 2021).

Another concern among insurers is rate competition with the NFIP. We heard in interviews that many customers only care about finding the cheapest flood policy, not about better coverage or other policy enhancements. This means that if a firm cannot undercut the NFIP, it essentially cannot operate in that area. The pricing practices used by the NFIP at the time of our study created many cross-subsidies in the program and so also multiple places where a private firm could potentially price lower than the program. Since then, the NFIP has adopted a new approach to pricing policies, Risk Rating 2.0, that better reflects risk at a property level. As we discuss below, it remains to be seen how this might impact private offerings. It is true that firms differ in their models, risk appetites, and the risk of their overall book of businesses, leading to varying underwriting and pricing strategies.

Although there has been concern about lenders accepting private flood insurance policies to comply with the mandatory purchase requirement, we did not hear this as a concern from many firms. Most private insurers told us that while they may have had to answer some initial questions or concerns, lenders were ultimately accepting of their products.

We heard that a large barrier to greater private market involvement in residential flood is that demand for flood insurance is quite low. Multiple stakeholders noted that homeowners' insurance companies received very little consumer pressure to offer flood and that it is difficult to sell flood coverage to those not required to purchase it. There was widespread support for improved risk communication and updated approaches to mapping flood risk to help increase demand for flood insurance.

3. Flood Insurance Demand

In the second phase of our work, this project undertook several sub-projects all aimed at better understanding flood insurance demand. This included a deep look at the mandatory purchase requirement, an investigation of flood insurance purchases outside the SFHA, and hosting a workshop on policy options to spur greater purchase and close the flood insurance gap.

3.1 The Mandatory Purchase Requirement

Since 1973 the purchase of flood insurance has been mandatory for residents of FEMA-mapped 100-year floodplains with a loan from a federally backed or regulated lender. In addition, those who receive federal assistance for property acquisition, construction, or repairs in a SFHA are required to purchase and maintain flood insurance or they will not be eligible for post-flood disaster assistance in the future. We conducted a close examination of the mandatory purchase requirement to better understand if was meeting its original objectives. For this study, we surveyed a sample of lenders to determine perceptions and opinions around the role of disaster insurance in the mortgage market, the efficacy of the mandatory purchase requirement, and lender interest in broader insurance requirements.

After the mandatory purchase requirement went into effect in 1973, the number of communities enrolled in the NFIP grew, as did the number of households with flood insurance. In 1969, there were just four participating communities and a mere 16 policies in force. By 1973, the program had grown slowly to encompass 2,850 communities and 312,000 policies. By 1977, after mandatory purchase went into effect, the number of participating communities quintupled to more than 15,000 and the number of policies nearly quadrupled, reaching 1.2 million. As of 2019, there were 22,384 participating communities and roughly 5.02 million policies in force. Thus, almost 75% of the current number of enrolled communities were already enrolled by 1979. In this sense, the requirement was effective in increasing community participation and purchase of flood insurance. (Shabman 2019)

To participate in the NFIP, communities must adopt minimum floodplain management regulations. In expanding the area of the country where new floodplain development was regulated, the mandatory purchase requirement also likely reduced flood damages. These regulations must require new construction to be at or above the FEMA estimated base flood elevation (the stage elevation for a 1% annual chance flood). No doubt this building code requirement has reduced flood damages relative to what they might have been without the regulations. That said, these regulations are felt by many to be insufficient. They only apply to new construction and fail to account for how flood risk is escalating as the planet warms. Finally, property owners outside the SFHA boundary often mistake the in-out line defining where the MPR does not apply as a place of low or non-existent flood risk.

There is a growing body of research that demonstrates those with insurance recover better and faster than those without insurance. Despite the value of flood insurance, the mandatory purchase requirement does not apply very widely. Within the SFHA, many residents are not subject to the requirement. According to the U.S. Census, at the time of our study, among the approximately 119 million occupied housing units in the U.S., 41% are occupied by homeowners with a mortgage, 23% by homeowners with no mortgage, and 36% by renters. Thus, if those percentages roughly hold in the SFHA, only about 40% of SFHA residents are required to purchase flood insurance. In addition, flood risk extends outside the SFHA—due to more extreme events, but also unmapped rainfall related flooding and out of date flood maps—and none of these

households are required to insure. There thus remains a large number of households at risk of flooding with no coverage.

Homeowners not subject to the requirement could still purchase flood insurance voluntarily, of course, but very few do. This could be due to lack of awareness of the risk, lack of funds to pay for flood insurance, or misunderstandings about insurance, among other reasons. One commonly discussed contributing factor is that the SFHA boundary line could lead homeowners to believe they are not at risk if they reside outside the 1% annual chance floodplain. While pricing has been updated in the NFIP since our project, the maps have not and still focus on delineating the SFHA. Still, there are indeed some residents who insure outside the SFHA. The next phase of the project investigated that segment of the market to better understand flood insurance demand among those voluntarily insuring.

3.2 Voluntary Purchase of Flood Insurance

In examining take-up rates of NFIP policies, we found there were many places around the country with a large share of total policies located outside SFHAs. Indeed, nationwide, just over half of all NFIP policies are outside the SFHA. There are numerous communities where most flood contracts are not in the SFHA. Some of these have very low absolute numbers of policies, but in other places, they can be quite sizable. For instance, in 2018, Fort Bend County, Texas has a total of 50,000 flood insurance contracts in force and 95% of them were outside the SFHA. Note, even in areas with a large share of policies outside the SFHA, the overall take-up rate outside the SFHA (that is, the share of all buildings outside the SFHA with flood insurance) is typically still very small, often in the single digits (Bradt 2021).

To better understand voluntary purchase of flood insurance, we undertook in-depth, semi-structured interviews and also administered an online questionnaire to community officials – such as floodplain managers, emergency managers, and city planners. We targeted officials in counties that had either a high share of all their flood insurance policies outside the SFHA or that had a high absolute number of policies in force outside the SFHA.

Across respondents, there were three frequently identified determinants of voluntary purchase outside the SFHA: (1) recent or repeated flooding outside the mapped SFHA; (2) active and continuing local outreach programs that educate the community about flood risk and availability and affordability of flood insurance; and (3) residents with enough personal disposable income to afford flood coverage. It appears the greatest voluntary demand is where residents have personal experience with the devastation and difficult recovery from flooding and/or are continually reminded of this by robust education and outreach. And, of course, flood insurance is expensive, and for many households it may simply be unaffordable. Since there is currently no program to assist low-income households with the cost of flood insurance, purchase is higher in areas of greater disposable income.

We explored flood insurance demand further in an econometric analysis of flood insurance purchases in and out of the SFHA between 2009 and 2019. We found that

households are responsive to prices, although minimally.[60] We joined flood insurance policy data to a more accurate and comprehensive measure of flood risk than FEMA maps and which included all sources of flooding (available from the First Street Foundation) and found that as that measure of flood risk increased, the probability of a household purchasing insurance rose dramatically, as did the average claim amount. This association is especially large outside the SFHA.[61] This is a strong indication of adverse selection driven by the failure of the NFIP to accurately capture flood risk in pricing, mapping, or the flood insurance mandate (Bradt 2021). This analysis, though, was conducted before the NFIP adopted their new pricing methods, which should better reflect household risk. Impacts of this price change are worthy of future study to see if it reduces adverse selection in the program.

3.3 Closing the Flood Insurance Gap

We undertook a day long workshop with key stakeholders to identify how the private sector, in partnership with the public sector, could help close the flood insurance gap in the United States and meet FEMA's "moonshot" goal of expanding the number of households covered by flood insurance. The workshop brought together roughly 50 experts across sectors and disciplines, including representatives from FEMA, the (re)insurance industry, lending institutions, state departments of insurance, non-profit organizations, and research institutions. Workshop participants identified seven approaches to closing the flood insurance gap that they felt had the potential, if designed appropriately, to lead to substantial increases in flood insurance purchase:

1. **a flood insurance opt-out**: Behavioral economics research has suggested that in certain circumstances, individuals stick with default options. Could flood insurance be made a default for some class of policyholders, leading to higher coverage levels? As flood insurance can be costly, leading to greater numbers opting-out, this may work best for lower-coverage endorsements in lower-risk areas.
2. **mandatory offer**: In this option, all insurance agents would be required to offer flood insurance when someone was purchasing a homeowners policy. The expectation was that greater awareness of flood could encourage more purchase.
3. **a federal backstop or reinsurance for flood**: Homeowners insurance excludes flood since it is a catastrophic peril and coverage for it is often more expensive than consumers will pay. One option is to follow the model of the

[60] Our results suggest that a 1% increase in the average price of non-SFHA policies results in a 0.290% decrease in the probability that a non-SFHA household purchases insurance and that a 1% increase in the average price of SFHA policies results in a 0.327% decrease in the probability that an SFHA household purchases insurance.

[61] We find that a 1 percentage point increase in the probability that a household is at risk of flooding according to the First Street Foundation model increases the probability of purchasing insurance by 369% and the average claim amount by 60% outside of SFHAs and increases the probability of purchasing insurance by 48% and the average claim amount by 58% inside of SFHAs.

Terrorism Risk Insurance Act, or the disaster risk approaches of countries such as France and Spain, and require flood in standard homeowners policies, but then provide a federal backstop to keep the costs lower and prevent insurer insolvency.

4. **community policies**: One notion that has been proposed to help close the flood insurance gap is for communities to purchase flood insurance on behalf of their residents in the floodplain. Such a policy would be purchased by a local governmental or quasi-governmental body and would cover a group of designated properties.
5. **insuretech to make purchase simpler**: Numerous workshop participants noted that currently it is difficult and time consuming to acquire an NFIP policy. Harnessing technological innovations in insurance (insuretech) to speed and ease purchase of flood insurance could have a positive impact on demand. If consumers could use an app on their phone to apply for and purchase a flood policy in less than 10 minutes, as well as manage all aspects of their policy, and receive flood preparedness information, many felt this could encourage more widespread purchase.
6. **escrowing monthly premiums and automatic renewal**: One concern voiced by participants was that policyholders may drop their flood policy over time. Some felt this was exacerbated by the fact that most NFIP policyholders are forced to actively renew each year and to make an annual
7. payment. Making renewal automatic and having premiums escrowed for homeowners insurance (this is indeed available) could lead to greater continuation of coverage.
8. **a voucher program for low- and moderate-income households**: Lower income households are most in need of the financial protection of flood insurance and least able to afford it. A federally-funded voucher program to help these households afford the cost of flood insurance could secure them greater financial resilience.
9. These concepts could be further explored in small pilots to test their impact on flood insurance demand and refine their design.

4. Implications to Risk Rating 2.0 for Our Study

Since we concluded this project in 2020, a major change has occurred in the NFIP – the adoption of Risk Rating 2.0 (RR2.0). This new approach to rating harnesses catastrophe models and improved data to price flood risk for each household. This is a dramatic departure from the NFIP's previous approach of pricing insurance largely based on large flood "zones," as well as certain structural characteristics of a property. With this change, the NFIP has modernized its rating and adopted pricing methods that match those used in the private sector. These new prices, when indicating a price increase for a property, are still subject to a Congressional cap on annual premium increases of 18%. While the program has better linked premiums with household level flood risk, the program is only managed to cover losses with a 1-in-20 year return interval, far below what a private firm would manage for in its pricing and reserving.

We briefly review what these changes could mean for the findings of our project.

Related to our project, one question is how RR2.0 will impact take-up rates for flood insurance. Important for improving equity, Risk Rating 2.0 removes a previous cross-subsidy in the program from low-value and high-valued homes. This change should make premiums less expensive for lower-valued properties and thus may improve the ability of some households to afford flood coverage. That said, for the first time in the program's history, risk-based premiums are being charged outside the SFHA. Prior to Risk Rating 2.0, these properties often received much lower flood insurance premiums. It remains to be seen how RR2.0 will impact voluntary purchase outside of the SFHA. Our research, though, also found that the cost of flood insurance only partly determines a household's decision on whether to voluntarily purchase coverage. Therefore, further expanding take-up rates in the presence of Risk Rating 2.0 will require renewed attention to programs that increase property owners' understanding of their flood risk and the value of purchasing flood insurance whether from the NFIP or a private seller.

Our report on the mandatory purchase requirement detailed how the 1% line was chosen at the beginning of the NFIP for defining the area of the floodplain where the NFIP minimum regulations had to be in place as a condition for a community participation in the NFIP. In 1973, when the MPR was created, it was a logical choice to use that same area for establishing the reach of the mandatory purchase requirement. These maps have become key flood risk communication products, despite being initially designed for regulatory purposes. While additional flood risk information is now being made more widely available by several other non-governmental groups, the flood maps continue to play a role in risk communication, particularly as the basis of many disclosure laws. Unfortunately, the area outside the 100-year floodplain often is mistakenly interpreted by many households as free of flood risk, or an area having minimal flood risk. The radically reduced NFIP premiums outside the SFHA may have reinforced this perception.

Motivated by the successful application of the analytical processes deployed in quoting property specific risk-based premiums for Risk Rating 2.0, FEMA has followed up with is Future of Flood Risk Data (FFRD) initiative, with goal of better communicating flood risk across the whole floodplain Risk Rating 2.0, combined with FFRD, could better communicate to communities and property owners who might voluntary purchase flood insurance that flood risk does not stop at the boundary for the SFHA. New analysis could also lead to a revision of the mandatory flood insurance requirement, to better target the purchase requirement to those at highest risk. This should be an area of future investigation.

A final question about RR2.0 that will need to be examined in the coming years related to our project work is the impact of this pricing change on the private residential market. We found that some private insurers had previously used cross-subsidies in the old NFIP rating structure to target areas where they could successfully compete against the program. It remains to be seen whether RR2.0 opens up more areas where firms can be cost competitive or instead closes off the areas where they

had previously been able to target market share. Despite those impacts, our conclusion that limited demand for flood insurance, whether NFIP or private, is the most significant constraint on growth in the private market, remains valid.

5. Conclusion

The NFIP is an important program nationwide, providing policyholders with financial resilience in the face of flood risk that is escalating in many locations. That said, the large flood insurance gap in the United States indicates that it is not providing needed financial protection to many at-risk residents. Over the past five decades, our ability to model, communicate, and transfer disaster risk has undergone many changes, and our technology and data for assessing and communication have greatly improved. The recent changes adopted in Risk Rating 2.0 can serve as a foundation for additional policy reform and program development to further close the flood insurance gap so that all households can obtain the financial protection provided by insurance.

6. Key Themes, Questions, and Additional Readings

6.1 Key themes

From this research effort, the following themes emerged:

- Very little data was available on the private flood insurance market and there were significant knowledge gaps in understanding the flood insurance gap, flood insurance demand, and policy options that may be available or other considerations that could help close this gap.
- This research served as a catalyst for motivating the National Association of Insurance Commissioners to begin collecting nationwide data to understand the private flood insurance market and demands signals.
- The private flood insurance market is emerging and states have implemented policies to try and cultivate this market as a complement to public flood insurance and risk reduction options.
- The private flood insurance market is dominated by reinsurance and key drivers of the market remain price and low demand.
- The mandatory purchase requirement (MPR) does not widely apply as only about 41% of the housing units in the SFHA are occupied by homeowners with a mortgage. This means most of the market is voluntary purchase. Just over half of the NFIP policies are located outside the SFHA.
- There were three frequently identified determinants of voluntary purchase outside the SFHA: (1) recent or repeated flooding outside the mapped SFHA; (2) active and continuing local outreach programs that educate the community about flood risk and availability and affordability of flood insurance; and (3) residents with enough personal disposable income to afford flood coverage.
- An econometric analysis of NFIP policy data with compound flood risk data found pricing had a minimal effect on households' uptake of flood insurance.

Household purchasing insurance rose dramatically, as did the average claim amounts suggesting a strong indication of adverse selection driven by the failure of the NFIP to accurately capture flood risk in pricing, mapping, or the flood insurance mandate.

- There is a growing body of research that demonstrates those with insurance recover better and faster than those without insurance.
- A larger number of road and bridge projects completed after Hurricane Floyd (measured as completed with FEMA Public Assistance funding) made communities more resilient than communities with fewer projects completed.

6.2 Discussion questions

- What is the NFIP and its key regulatory components?
- How is the SFHA determined and what does it define?
- What is an econometric analysis and how was it used by the researchers to examine the NFIP?
- What were the seven approaches identified for closing the flood insurance gap that were considered by the researchers?
- What are some of the key implications of this research to the NFIP and risk rating 2.0?

6.3 Additional Readings

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Options for closing the insurance gap and increasing financial preparedness

Lloyd Dixon, Jason Barnosky, and Noreen Clancy[62]

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Abstract

Federal, State, and local governments share responsibilities for managing disaster risk and recovery costs. Over time more of the disaster risk share has shifted to the federal government. A significant portion of disaster costs falls on the Federal Emergency Management Agency (FEMA), the agency responsible for leading federal disaster response and recovery. FEMA's largest programs is the Public Assistance (PA) grant program, which provides funding to support debris removal; emergency protective measures; and the repair, replacement, or restoration of facilities that are publicly owned or owned or operated by certain private nonprofit (PNP) organizations. FEMA also administered the National Flood Insurance Program (NFIP) and reinsurance to cover direct losses for homeowners impacted by flooding. This paper explores questions on how best to manage disaster risk and whether the current allocation of risk between the different levels of government are appropriate, what are the most common state and local financial risk-management practices and the role that FEMA's PA program plays in these decisions as well as opportunities to leverage financial preparedness and insurance markets in closing these gaps or improve federal disaster assistance programs.

Keywords

Insurance, finance, policy options

1. Introduction

"If effectively designed, risk transfer mechanisms such as insurance products can even incentivize active risk reduction by policy holders." (Jongman 2018)[63]

In the United States, federal, state, and local government share responsibility for managing disaster risk. Traditionally a state and local function, more and more responsibility for the cost of recovery has shifted to the federal government over time, and federal programs providing support to state and local entities for disaster response

[62] Lloyd Dixon, Jason Barnosky, and Noreen Clancy

[63] Jongman, B. (2018). Effective adaptation to rising flood risk. *Nat Commun* 9, 1986 (2018). https://doi.org/10.1038/s41467-018-04396-1

and recovery have proliferated.[64] How best to manage this risk and whether the current allocation of risk between the different levels of government are appropriate is much debated—as disaster costs pose significant challenges to the public sector. For example, the U.S. Government Accountability Office (GAO) has pointed to disaster costs as a key source of federal fiscal exposure, noting that federal funding for disaster assistance has approached half a trillion dollars since 2005. GAO has further stated that disaster costs are projected to increase as extreme weather events become more common.[65]

At the federal level, a significant portion of disaster costs falls on the Federal Emergency Management Agency (FEMA), the agency responsible for leading federal disaster response and recovery. One of FEMA's largest programs is the Public Assistance (PA) grant program, which provides funding to support debris removal; emergency protective measures; and the repair, replacement, or restoration of facilities that are publicly owned or owned or operated by certain private nonprofit (PNP) organizations. One category eligible for PA funding includes buildings, contents, vehicles, and equipment (BCVE). In recent years, FEMA has sought to shift risk away from the federal government. For example, during the Trump administration, FEMA prioritized transferring more risk to the private sector by closing the insurance gap—that is, the difference between what is currently insured and what is insurable—for communities, individuals, and businesses.[66] Across the United States, a significant insurance gap exists. Residences are often uninsured, for example. A 2018 FEMA analysis showed that 53 percent of homeowners in high-risk flood zones lacked flood insurance.[67] And only about 10 percent of homes in California have earthquake insurance.[68]

Managing public-sector disaster risk involves considering a variety of trade-offs. Shifting a greater portion of disaster costs to state and local entities could encourage them to adopt mitigation measures or transfer risk to the insurance market, which—when claims are expeditiously resolved—would enable survivors to get back on their feet quickly and promote fast recoveries for affected communities. However, private insurance markets do not always function well, especially for extreme events, and leaving responsibility with the federal government ensures that these risks are spread widely. Figure 1 provides a framework for conceptualizing the allocation of risk between the different levels of government and identifies some of the advantages and disadvantages of different allocations.

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[64] For an overview of the evolution the federal government's role in emergency management, see Patrick Roberts, "FEMA After Katrina" and "Our Responder in Chief."

[65] Thomas Frank, "Why the U.S. Disaster Agency Is Not Ready for Catastrophes;" GAO, *U.S. Virgin Islands Recovery*, 110 and 113.

[66] FEMA, *Strategic Plan*, 15; Daniel Kaniewski, "Using Innovative Technology and Practices," 5.

[67] FEMA, *An Affordability Framework for the National Flood Insurance Program*, 14. The percentage with flood insurance can be calculated from the numbers presented in FEMA, 2018b, Table 2.6. The 53-percent estimate does not include private flood policies, which somewhat lower the percentage without insurance.

[68] Eric Westervelt, "Quake Insurance?"

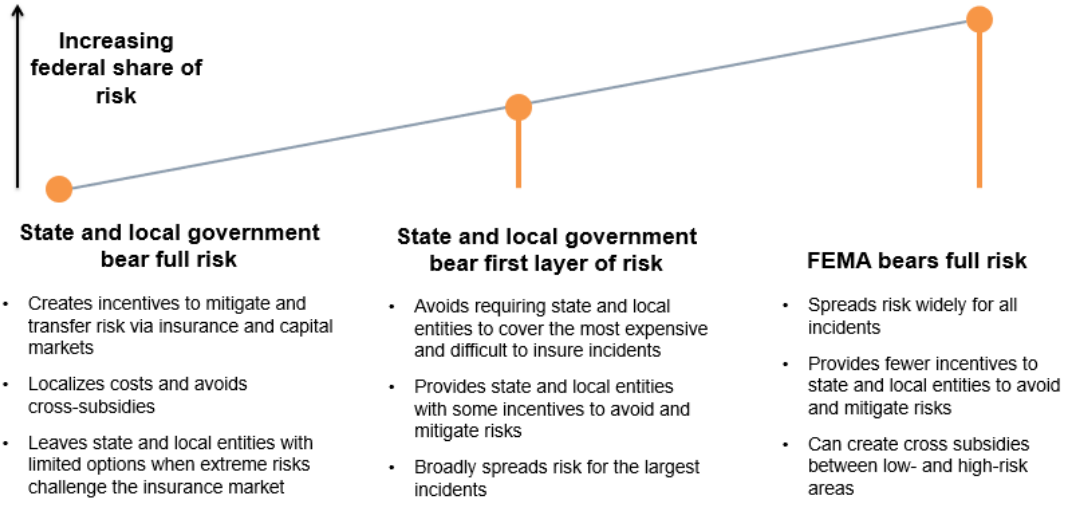


Fig. 1: *A Risk Allocation Framework*

In this chapter, we aim to contribute to this debate by improving our understanding of state and local financial risk-management practices and the role that FEMA's PA program plays in these decisions. Little systematic data exists on insurance practices for public facilities.[69] Consequently, it is difficult to characterize how state and local governments manage their risk and what can be done to encourage better risk-management practices. Our analysis provides insight into what state and local governments are doing to manage risk to their facilities—specifically, their BCVE—and how FEMA PA funding contributes to these decisions. We also discuss different approaches for sharing risk between federal, state, and local government and the trade-offs associated with them. In doing so, we hope to shed light on what can be done to address public-sector disaster risks and the costs associated with them.

2. Research Questions and Study Approach

Our analysis addresses three research questions:

1. What insurance and financial risk-management practices do state and local governments employ for BCVE?
2. What role does FEMA assistance play in these decisions?

[69] On this point, see Adam Rose et al., "The Role of a Deductible/Credit System," 5.

3. What are options for closing the insurance gap for BCVE?

For each research question, we drew on interviews with FEMA staff and conferred with insurance brokers who served as part of the research team. Brokers often work with state and local governments to help them determine the right level of insurance, and, through these relationships, they gain insight into state and local risks and needs. More than 20 FEMA staff and ten insurance brokers contributed their expertise to the project. We conducted a literature review, including key policy documents and analyzed data from FEMA's Emergency Management Mission Integrated Environment (EMMIE) database. Because the Paperwork Reduction Act limited our ability to interview state and local officials, we also developed, executed, and assessed the results of a request for information (RFI) on state and local government financial risk-management practices, as well as the insurance products available to them. We received six responses to the RFI. Table 1 provides our methodology for each research question in more detail.[70]

Table 1. Our Methodology, by Research Question

Research Question	Methodology
1. What insurance and financial risk-management practices do state and local governments employ for BCVE?	• Conduct a literature review on state and local risk-management practices. • Interview FEMA headquarters and regional staff. • Confer with insurance brokers. • Review the EMMIE database for information on state and local insurance and risk-management practices. • Develop an RFI and analyze the results.
2. What role does FEMA assistance play in these decisions?	• Conduct a literature review on the impact that disaster assistance has on insurance decisions. • Interview FEMA headquarters and regional staff. • Confer with insurance brokers. • Develop an RFI and analyze the results.

[70] Additional detail on the methodology can be found in Lloyd Dixon, Jason Thomas Barnosky, and Noreen Clancy, *Insuring Public Buildings, Contents, Vehicles, and Equipment Against Disasters.*

Research Question	Methodology
3. What are options for closing the insurance gap for BCVE?	• Conduct a literature review on policies and practices for encouraging the purchase of insurance. • Interview FEMA headquarters and regional staff. • Confer with insurance brokers.

Our analysis has several limitations. Although state and local governments own and operate a variety of types of facilities, we restricted our analysis to BCVE—what FEMA refers to as category E in its PA program. The other categories of permanent work for the PA program include types of facilities—such as roads, bridges, and water control facilities—for which obtaining insurance is much more difficult or might not exist. In contrast, insurance policies for BCVE are available today from the private insurance market. Another limitation concerns the pool of PA applicants we considered. Although the PA program is open to tribes, territories, PNPs, states, and localities, we evaluated only the latter two types of entities. Tribes and territories accounted for too small a portion of the observations in our data set—approximately 200 of the 15,000 observations we analyzed—for us to be able to conduct robust analysis. PNPs composed about 19 percent but given the diversity of the nonprofit pool—which includes organizations ranging from hospitals and universities to churches and day care centers—PNPs posed methodical challenges beyond the scope of this study.

2.1 The Public Assistance Program and the Allocation of Risk Between Federal, State, and Local Governments

Disaster assistance programs offer public-sector organizations a tool for sharing risk with different levels of government. At the federal level, FEMA serves as the agency responsible for leading disaster response and recovery efforts, and the agency administers multiple programs providing disaster assistance to state and local governments—including the PA grant program. Established through the Robert T. Stafford Disaster Relief and Emergency Assistance Act, the PA program is one of the most important federal programs supporting disaster response and recovery and FEMA's largest.[71] Between fiscal year (FY) 1999 and the third quarter of 2019, the agency obligated approximately $89 billion through the program.[72]

Two broad types of activities receive funding through the PA program: emergency work and permanent work. Emergency work is an activity that addresses an immediate threat, while permanent work is an activity that restores a damaged facility. FEMA separates these two types of work into seven categories—categories A through G—two

[71] GAO, *Disaster Assistance*, 2; Public Law 93-288. *Disaster Relief Act Amendments*

[72] FEMA, "OpenFEMA Dataset."

of which fall under emergency work and five of which fall under permanent work. Table 2 identifies these seven categories.

Table 2. Categories of Public Assistance Work

Category	Description
Emergency work	
A	Debris removal
B	Emergency protective measures
Permanent work	
C	Roads and bridges
D	Water control facilities
E	BCVE
F G	Utilities Parks, recreational, and other facilities

For permanent work, FEMA obligates the largest share of funding to PA category E, BCVE. Between FY 1999 and the third quarter of 2019, PA category E received $19 billion in obligations—22 percent of the total. Table 3 provides PA obligations by work category.

Table 3. Public Assistance Grant Program Obligations, by Category of Work, Fiscal Year 1999 Through the Third Quarter of 2019

Category	Total Obligations, in Billions of Dollars	Percentage of Total
Emergency work		
A. Debris removal	14	16
B. Emergency protective measures	24	27
Permanent work		

Category	Total Obligations, in Billions of Dollars	Percentage of Total
C. Roads and bridges	9	10
D. Water control facilities	1	1
E. BCVE	19	22
F. Utilities	12	14
G. Parks, recreational, and other facilities	4	5
Recipient management costs[a]	5	6
Total	89	100

SOURCE: FEMA, 2015a.

[a] FEMA allows recipients and subrecipients of PA funding to use a portion of their funding for indirect expenses, administrative expenses, and other expenses for managing a PA award that they cannot charge to a specific project. FEMA refers to these costs as category Z. See FEMA, 2020a, p. 147.

FEMA awards PA funding directly to state, tribal, and territorial governments (applicants). These entities may then pass this funding on to subapplicants—which include the approximately 90,000 local governments in the United States.[73] According to one estimate, these local governments together own more than 3 million buildings.[74] PNPs that provide critical or essential social services are also eligible to be subapplicants. These can include such entities as universities, hospitals, and houses of worship.[75]

2.2 Public Assistance Award Process

The issuance of PA funding begins with a presidential disaster declaration. Once the President has issued a declaration for a geographic area—such as a county, city, or Indian tribal government—state, tribal, and territorial governments work with FEMA to assess the damage and identify projects eligible for the PA program. The Stafford Act

[73] The local government figure comes from Carma Hogue, *Government Organization Summary Report, 1.* FEMA uses applicant to refer to the states that formally apply for PA assistance and subapplicant for the counties, cities, and other public entities that apply through the state. For simplicity, we use applicant to refer to all these entities in the remainder of this report. In 2013, the Sandy Recovery Improvement Act (Pub. L. 113-2) amended the Stafford Act to create an additional process for providing PA funding.

[74] Littman, "Solving the Mystery."

[75] FEMA, *Public Assistance Program and Policy Guide,* 10–13. The risk-management behaviors of PNPs are not addressed in this report.

generally prohibits the duplication of benefits.[76] In the case of insurance, for instance, if an applicant has received—or anticipates receiving—proceeds for losses, FEMA deducts that amount from the repair costs, and the remainder is the project amount.[77] After FEMA approves a project, PA essentially functions as a reimbursement program: The agency obligates funding to the applicant, which is a state, tribal, or territorial government. The applicant can then provide funding to the subapplicant—local government or certain PNP organizations—for projects they have completed. Risk sharing is another key element of the program. As a condition of receiving PA, the recipient is responsible for a cost share under which the recipient pays 25 percent of the project amount and FEMA pays the remaining 75 percent.[78] States administer this cost share in a variety of ways, differing in the extent to which localities are responsible for part of it.[79]

2.3 Requirement to Obtain and Maintain Insurance

The Stafford Act requires that as a condition of receiving PA funding, an applicant must obtain and maintain (O&M) insurance for a damaged facility for the life of the facility to protect against future losses.[80] Specifically, the applicant must insure such a facility with the "types and extent" of insurance that are "reasonably available, adequate, and necessary."[81] If an applicant does not meet the O&M requirement, FEMA denies or deobligates funds for the immediate disaster, and the facility will be permanently ineligible for PA funding.[82] FEMA applies the O&M requirement only to BCVE because it has concluded that insurance is not readily available for other types of public facilities.

FEMA administers the O&M requirement through insurance reviews to determine whether an applicant previously received PA for a damaged facility and, if so, whether the applicant has complied with its insurance requirements. For applicants that have not received PA previously, FEMA provides a notification outlining the type and extent of insurance required. Concerning insurance type, FEMA requires an applicant to obtain insurance against the hazard that caused the damage—an earthquake, for example. If multiple hazards caused the damage, the applicant must insure against each of them.[83] To determine the extent of insurance required, FEMA calculates the

[76] See 42 U.S.C. § 5155. Under some conditions, the President may waive this prohibition.

[77] FEMA, *Public Assistance Program and Policy Guide*,, 39-40; 44 C.F.R. § 206.253(a).

[78] The President, through FEMA, has the discretion to increase the federal cost share to as much as 90 percent for permanent work and more for emergency work. FEMA, *Public Assistance Program and Policy Guide*, 3–4.

[79] National Emergency Management Association, *NEMA 2016 Biennial Report*, 10.

[80] 42 U.S.C. § 5154.

[81] 42 U.S.C. § 5154.

[82] FEMA, *Public Assistance Program and Policy Guide*, 87.

[83] FEMA, *Public Assistance Program and Policy Guide*, 86; FEMA, "Public Assistance Policy on Insurance," 4.

estimated or actual costs eligible for PA funding as a result of that disaster prior to any reductions, such as from insurance proceeds.[84]

Once FEMA has determined the type and extent of insurance an applicant requires, the applicant can choose the policy it finds most appropriate.[85] In most cases, an applicant can also employ a self-insurance plan to meet the O&M requirement. Under some circumstances, FEMA can modify the requirements for applicants. For example, an applicant may request that FEMA modify its requirements if the applicant has tried to comply but found that such insurance is unavailable, an alternative provides adequate protection, or the required insurance is not necessary.[86] Similarly, FEMA will not require greater types or extent of insurance than the relevant state insurance commissioner deems reasonably available, adequate, or necessary, and the agency will modify an applicant's insurance requirement based on a state insurance commissioner's certification of these factors.[87]

In making its PA award, FEMA deducts insurance proceeds. The first time a facility has been submitted to the PA program, FEMA deducts the anticipated insurance proceeds (which means that it, in effect, pays the deductible) and then makes a final reduction to match the actual amount of insurance.[88] For a facility subject to an O&M requirement, FEMA deducts either the amount of insurance in the O&M requirement or the actual insurance proceeds for eligible losses, whichever is higher.[89] FEMA also does not pay the deductible in these instances.[90] FEMA thus does not pay a second time for losses at a facility up to the O&M requirement from the previous event, regardless of whether the applicant purchased insurance.

3. Definition and Measurement of Insurance Share

In this section, we define *insurance share*. We then discuss issues that arise when evaluating insurance share using FEMA's data on PA expenditures. The section concludes with an overview of data that underlie the analysis.

3.1 Definition of Insurance Share

Insurance policies are typically structured with a deductible and policy limit. As shown in the left panel of Figure 2, insurance payment is 0 until the deductible is reached and then increases one-to-one with repair costs until repair costs reach the policy limit. The resulting ratio of insurance payments to repair cost—the insurance share—is shown in the right panel of Figure 2. The share begins as 0, increases once repair costs exceed the deductible, and then declines once repair costs exceed the

[84] FEMA, "Public Assistance Policy on Insurance," 3.

[85] FEMA, *Disaster Operations Legal Reference*, 5-103–5-104.

[86] FEMA, "Public Assistance Policy on Insurance," 5.

[87] FEMA, "Public Assistance Policy on Insurance," 6–7.

[88] FEMA, *Disaster Operations Legal Reference*, 5-107.

[89] FEMA, *Public Assistance Program Management and Grant Closeout*, 87; FEMA, *Disaster Operations Legal Reference*, 5-107.

[90] FEMA, "Public Assistance Policy on Insurance," 9.

policy limit. For example, if repair costs were $500,000 and the public entity received $200,000 from the insurer, the insurance share would be 40 percent. The insurance share for a given repair cost can vary from 0 (when no insurance is available) to close to 100 percent (when the deductible is small and repair costs do not exceed the policy limit).

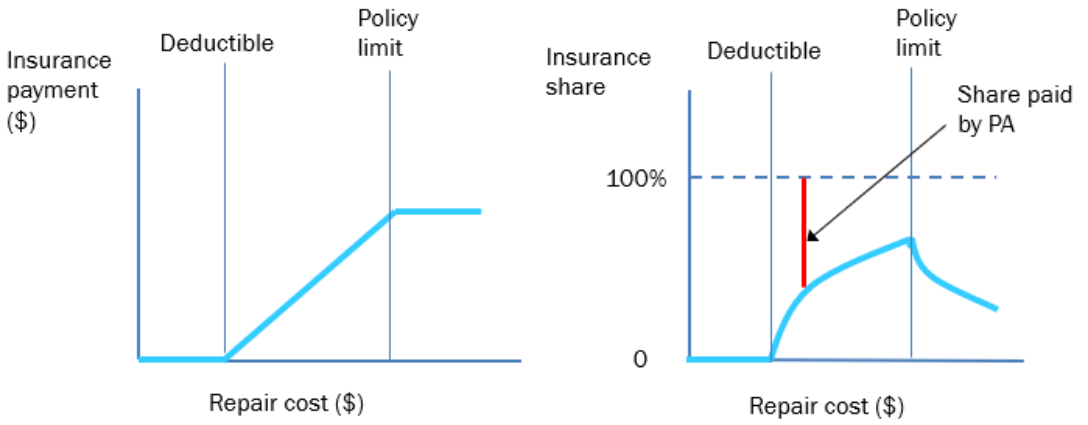


Fig. 2: *Typical Relationship Between Insurance Share and Repair Costs*

NOTE: Our definition of *insurance share* includes payments by insurers and other insurance-related reductions that FEMA makes.

So far, we have presented insurance from the point of view of a public entity holding the insurance. We now turn to FEMA's perspective. When the PA program pays the deductible (as it does for first-time losses), the portion of repair cost covered by PA is the difference between the blue curve in the right panel of Figure 2 and the dotted line at 100 percent. If FEMA pays losses over the policy limit but does not pay the deductible (as would be the case for insurance bought in order to comply with the O&M requirement), the portion of loss paid by FEMA would start at 0 and remain at 0 until the policy limit is reached. It would then increase at a decreasing rate as repair cost increases above the policy limit.

The definition of *insurance share* we use in this study includes some repair costs for which the applicant does not receive an insurance payment but for which FEMA will not pay. For example, insurance share includes the deductible when coverage is mandated by the O&M requirement because the PA program will not cover the deductible in these circumstances. Insurance share also includes required reductions for flood-related damage in a special flood hazard area (SFHA) up to the coverage limits provided by the National Flood Insurance Program (NFIP) regardless of whether the applicant purchased flood coverage or how much was purchased. However, the

magnitude of these adjustments recorded in EMMIE is small.[91] *Insurance share* as used here in effect identifies the portion of the repair costs that PA will not pay, prior to the application of the state cost share. It reflects the amount of insurance the applicant had or should have had on the damaged property according to PA policy.

Our definition of *insurance* captures only the formal or observed insurance held by public agencies—which becomes manifest in insurance reimbursement for loss. It does not include rainy-day funds or other resources that some agencies, particularly larger ones, may bring to bear in a disaster. Such a definition is relevant to projecting PA program outlays and assumes, in effect, that the PA applicant has no unobserved or hidden insurance. However, it may be the case that some entities have additional resources that function very much like insurance.

3.2 Measurement of Insurance Share

FEMA uses the EMMIE system to process PA grant applications. In August 2019, the Recovery Analytics Division (RAD) in FEMA's Office of Response and Recovery provided us with detailed EMMIE data on PA category E projects. The data cover PA projects for which federal dollars have been obligated and include projects for disaster declarations between late 2007 through April 2019. Because the number of entries in 2007 was so small, we restricted our attention to PA projects for disaster declarations that occurred on or after January 1, 2008. To reduce the number of projects with preliminary or incomplete cost estimates, we excluded projects for declarations occurring after June 30, 2018.

We used EMMIE to provide insight into the insurance on BCVE owned by public entities eligible for PA. Some caveats are needed. To characterize insurance practices, one would ideally want data on a random sample of communities and structures across the country. The EMMIE data differ from this ideal in several ways:

- First, EMMIE provides data on BCVE only in communities for which major disasters were declared during the study period. These communities are presumably at higher risk of natural disaster than a random sample of all communities across the country. To the extent that a community that has been included in a disaster declaration is at higher risk than one that has not, it would be appropriate to characterize findings from the EMMIE data as describing the situation in the higher-risk parts of the country.
- Second, EMMIE does not provide a random sample of BCVE in communities that have been affected by major disasters. FEMA generates EMMIE data only for damaged BCVE for which PA applications have been submitted. For example, it could be that applicants do not submit PA applications for properties that have substantial insurance. Interviews with PA staff indicated that FEMA encourages applicants to submit all damaged buildings to the

[91] The extent to which such reductions are identified in EMMIE (as opposed to being lumped together with actual insurance payments) depends both on the extent to which such reductions are first enforced and on the extent to which they are entered with the correct cost codes in EMMIE. It could be that these types of reductions are larger than can be detected in EMMIE.

program regardless of insurance, mitigating this potential bias. Applicants have an incentive to do so because FEMA uses the total amount of damage, before reduction due to any insurance payments, to determine the amount of mitigation assistance for which a community is eligible. FEMA staff believe that applicants typically include all damaged BCVE in PA applications, but we heard of exceptions during our investigations. The insurance shares reported here are low to the extent that applicants do not submit damaged buildings with high levels of insurance to PA.

- Finally, BCVE damage (and thus the likelihood that the BCVE damage appears in the EMMIE database) may be correlated with the amount of insurance in place on the building. For example, an applicant might buy more insurance on a building in a riskier part of the community. But because insurance is more expensive on buildings at greater risk, an applicant might alternatively buy less insurance on a risky building. Thus, the direction of a potential bias in estimates of the amount of insurance is not obvious. In addition, communities can buy blanket policies that insure all their structures, thus mitigating concern that only the more (or less) risky buildings are insured.

Repairs at multiple separate facilities can be bundled together into a single PA project, but FEMA reports cost and insurance information in EMMIE only at the project level. Even though costs are available at the project level, we chose applicant–declaration pair as our unit of analysis. An applicant–declaration pair combines all the PA category E projects for a particular applicant in a disaster declaration. We chose applicant–declaration pair as the unit of analysis because applicants often have blanket insurance policies that cover all buildings, vehicles, or equipment (or some combination of these) in their jurisdictions. It therefore does not make sense to apply the insurance deductible or the policy cap to an individual project or facility.

As shown in Table 4, we have identified 11,561 applicant–declaration pairs for disasters declared between January 1, 2008, and June 30, 2018. Although most applicants applied for PA assistance in one disaster declaration during this period, some applied for assistance in multiple declarations. Consequently, just over 8,900 unique applicants appear in the database, with applications submitted in 500 unique disaster declarations.[92] There are nearly 40,000 projects in the database, amounting to 3.4 projects per applicant–declaration pair on average.[93] Projects, in turn, can involve repair or replacement of one or more facilities, and there are 1.6 facilities per project on average. A facility might be a city hall, a university building, a vehicle, or any of various types of equipment.

[92] A single disaster can result in multiple disaster declarations. A separate declaration is typically issued for each state affected by an event. For example, Hurricane Sandy resulted in separate declarations in ten states (Connecticut, Delaware, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and West Virginia) and the District of Columbia that resulted in category E applications.

[93] Each project-level record is also referred to as a project worksheet.

Table 4. Overview of Public Assistance to State and Local Government for Buildings, Contents Vehicles, and Equipment (for Disaster Declaration Dates January 1, 2008, to June 30, 2018)

Feature	Value
Applicants, declarations, and facilities	
Applicant–declaration pairs	11,561
Unique applicants	8,909
Unique disaster declarations	500
Projects	39,168
Facility–project pairs	64,573
Cost component, in billions of dollars	
Repair costs	9.39
Insurance reductions	2.65
Mitigation costs	2.40
Administrative costs	0.21
Project amount	9.36

4. Findings

What Insurance and Financial Risk-Management Practices Do State and Local Governments Employ for Buildings, Contents, Vehicles, and Equipment?

We found that a significant portion of state and local governments eligible for PA purchase insurance for their BCVE. However, data limitations prevent precise estimates of the take-up rate. Although insurance appears to be common overall, the average insurance share for applicant–declaration pairs is 46 percent. And, because the insurance share is much lower for larger losses, the proportion of overall repair costs covered by insurance is only 28 percent, which suggests that insurance is not covering a substantial portion of BCVE repairs. When we look closely at these figures, we see differences by jurisdiction type and size.[94] At 44 percent, the insurance share for cities is much higher than the average for states (27 percent). And the average for smaller

[94] Jurisdiction here refers to a city, county, state, or other public entity, such as a school district, that is eligible to apply for PA funding.

jurisdictions is much higher than for larger ones, falling from 48 percent for jurisdictions with populations less than 50,000 to 26 percent for jurisdictions with populations greater than or equal to 1 million.

To help us understand what drives this variation in insurance share, we used regression analysis to isolate the effects of different incident and public-entity attributes. Our findings were generally consistent with the observations of experts with whom we conferred.

4.1 Repair Cost Per Capita

An applicant's total repair cost per capita in a particular declaration is a measure of incident severity that allows comparison across jurisdictions of different sizes. As shown in the first row of Table 5, we found that insurance share increases considerably as repair cost per capita increases. This increase is consistent with FEMA covering the applicant's insurance deductible and the applicant's insurance covering remaining losses up to policy cap. Deductibles can be large, resulting in substantial federal payment for this first level of loss.

Table 5. Summary of Relationship Between Incident and Applicant Attributes and Insurance Share for Buildings, Contents, Vehicles, and Equipment

Attribute	Relationship Between Insurance Share and Attribute	Range of Predicted Insurance Share
Incident		
Size of loss per capita	Increases as repair cost per capita increases	16–59% over the range of per capita repair cost observed
Type of peril	Lowest for earthquake and flood	15% for earthquake and 25% for flood; 50% for storms without flood
Location in an SFHA	Lower for flood outside SFHAs	22–38% for flood-only events, based on the percentage of damage outside SFHAs
Property type	Lower for equipment than for buildings, contents, and vehicles	34–42%, depending on the percentage of damage attributable to equipment
Public entity		
Jurisdiction size	Highest for midsized jurisdictions, lower for smaller and larger jurisdictions. Higher repair cost per capita in small jurisdictions brings up the insurance share for the smallest jurisdictions.	33% for smallest jurisdictions, rising to 47% for midsize jurisdictions, then dropping to 31% for the largest jurisdictions[a]

Attribute	Relationship Between Insurance Share and Attribute	Range of Predicted Insurance Share
Frequency of prior disaster declarations	Higher in jurisdictions with a substantial number of disaster declarations in the prior five years, but declines as the number of declarations more than five years prior to current declaration grows	40–46%, depending on the number of declarations in the prior five years; 34–43%, depending on the number of declarations more than five years prior to the incident
[a] The 31% for the largest jurisdictions is the average of the predicted shares (details in Chapter Four), excluding the prediction for repair costs <$0.25 per capita.		

4.2 Type of Peril

Insurance share varies importantly by peril type. The very low insurance share for earthquake combined with the high value of assets exposed means that earthquakes present a major financial exposure for the federal government. Limited flood coverage remains a challenge, with insurance share for flood losses substantially lower than for losses not involving flood.

4.3 Location in a Special Flood Hazard Area

Our analysis suggests that insurance share for flood losses is lower outside SFHAs, which are FEMA-designated areas with at least a 1-percent annual chance of flooding, essentially the riskiest areas for flooding. The results are not particularly convincing, however. The standard errors of the estimates are large, driven by the relatively small number of applicant–declaration pairs for flood-only incidents.

In contrast to this finding, the experts with whom we conferred generally indicated, flood coverage is higher outside SFHAs. However, this inconsistency could be, in part, due to a feature of the PA program that increases our measure of insurance share inside an SFHA. Specifically, PA deducts the amount of insurance that an applicant could have purchased from the National Flood Insurance Program regardless of whether flood insurance was purchased for structures in an SFHA. Our measure of insurance share includes these reductions and could, in principle, cause measured insurance share to be higher inside than outside an SFHA.

4.4 Property Type

Insurance share appears lower for equipment than for buildings, contents, and vehicles. However, equipment repair costs do not account for a substantial share of overall repair costs.

4.5 Jurisdiction Size

Insurance share is highest for the smallest jurisdictions and declines considerably as population increases. Insurance share is approximately 48 percent for jurisdictions with populations less than 5,000; 5,000 to 10,000; and 10,000 to 50,000. It then falls steadily to 26 percent for jurisdictions with population greater than or equal to

5 million. This steady decline, however, appears due in part to variation in other factors besides population. When other applicant and incident attributes are held constant, insurance share peaks for jurisdictions with populations between 10,000 and 50,000 and is lower for both smaller and larger jurisdictions.

The lower insurance share for larger communities might reflect increased use of risk-management tools that are less readily available to smaller communities. For example, larger communities can more readily set up rainy-day funds to repair disaster damage, borrow postevent to repair uninsured damage, or rely on postevent tax increases to cover losses. Our measure of insurance share does not capture these and other types of risk-management approaches. This unobserved or hidden insurance, which is sometimes referred to as self-insurance, is difficult for FEMA to document and is not deducted from PA awards—even though it can be called on when FEMA PA funding is not available. The result is a lower insurance share for large communities but not necessarily less capacity than smaller communities to address losses. Having these types of self-insurance available means that larger communities are benefiting more from FEMA PA because they can adopt a risk-management approach that maximizes FEMA assistance. An important priority for policymakers is understanding how to address these types of self-insurance when determining eligibility for assistance.

Financial constraints in small communities might be responsible for the fact that insurance shares are lower in small communities than in midsized ones when other incident and applicant attributes are held constant. One reason that the observed insurance share (the insurance share before correcting for other incident and applicant characteristics) is higher for small communities than midsized ones is that smaller communities tend to have higher repair costs per capita than larger communities. As discussed above, higher repair costs per capita are associated with higher insurance shares, raising the observed insurance share for small communities. Further work is needed to better understand the causes for and implications of the higher repair cost per capita of smaller communities in declared disasters.

4.6 Frequency of Prior Disaster Declarations

We also found that applicants who have experienced a substantial number of disaster declarations in the five years prior to the current incident have higher insurance share than those with fewer declarations. What is surprising is that insurance share falls as the number of declarations more than five years prior to the current incident increases. The differences are not large, however, and are not estimated with a great deal of precision. The pattern suggests that insurance share is lowest in the high-risk areas where FEMA spends the most. The findings suggest that discussion of insurance practices in repetitive loss areas should be a priority.

What Role Does FEMA Assistance Play in the Risk-Management Decisions of State and Local Government?

Scholars have explored the relationship between disaster assistance programs and the purchase of insurance, but their work has not provided firm conclusions as to

whether postdisaster assistance discourages public-sector entities from purchasing insurance. In contrast, the predominant view among the FEMA staff and insurance brokers with whom we consulted was that the potential for FEMA assistance reduces insurance purchases by state and local government. At one extreme, experts pointed to public entities that do not buy any catastrophic coverage. These entities view public buildings as essential facilities and believe that it is FEMA's responsibility to get essential facilities up and running after a disaster.

Experts familiar with the risk-management thinking and decisions of state and local government also noted less extreme responses. Some public entities buy insurance for only the facilities that they believe are critical to repair quickly. Examples include police and fire stations and critical administrative buildings. These public entities rely on the PA program to repair or replace the rest. It was also commonly believed that state and local governments that do purchase coverage buy less than they would absent the PA program. For example, a county might buy coverage adequate to cover a 1-in-100-year event and rely on FEMA to cover larger events. The county realizes that FEMA assistance would not be available for events that do not rise to the level of a presidential declaration but would be available for the largest events. Such entities recognize that they are underinsured but conclude that the gap is acceptable because FEMA assistance will likely be available for large events. Experts also observed that some state and local governments select larger deductibles than they would otherwise, knowing that PA will cover the deductible for first-time losses.

The circumstances and risk-management practices of state and local government are diverse, and some experts also saw no evidence that some bought less insurance because they expected that FEMA would bail them out, and several noted that some state and local governments are reluctant to rely on FEMA. Were FEMA to eliminate PA for BCVE, experts with whom we spoke stated consistently that the extent to which communities believe that such a policy change was permanent would be a key factor in determining how they respond. But experts offered different perspectives on how, were such a policy change successful, it would affect state and local behavior. Experts argued that it would have little impact on public entities in some cases, but a more common view was that state and local governments would take more responsibility for managing their disaster risks.

What Are Options for Closing the Insurance Gap for Buildings, Contents, Vehicles, and Equipment?

Throughout our research, we asked subject-matter experts to identify approaches that could encourage state and local governments to purchase insurance for their BCVE. Four approaches emerged, which we summarize in Table 6. First, experts recommended requiring credit rating agencies (CRAs) to evaluate communities' financial preparedness for disasters. They noted that, in assessing a community's creditworthiness, CRAs do not generally evaluate this and that encouraging CRAs to do so could create an incentive for communities to adopt better financial risk-management practices. Second, experts suggested requiring state and local governments to analyze and disclose information on their vulnerabilities to the

hazards they face, noting that they often do not have a good understanding of their economic consequences. Such a requirement could increase their awareness of their risks, promoting better mitigation and enabling the private sector to develop appropriate solutions. Third, experts argued for holding state and local governments responsible for the first layer of loss to BCVE, suggesting that communities obtain coverage for up to 1-in-100 or 1-in-200-year events. PA funding would be available only for losses over this threshold, creating an incentive for state and local governments to mitigate their risks. Finally, another option would be to end eligibility for BCVE to receive PA funding, such as was proposed during the Trump administration. Under such an approach, state and local governments would become responsible for bearing all the costs of repairing or restoring BCVE, which could encourage mitigation and potentially lower the overall risk communities face. It would also render moot discussions about whether larger entities have self-insurance that FEMA should deduct from PA awards. However, eliminating PA would leave state and local governments responsible for managing the largest incidents, which can be difficult and expensive to insure.

Table 6. Overview of Options for Encouraging State and Local Governments to Purchase Insurance for Public Buildings, Contents, Vehicles, and Equipment

Option	Description	Advantages	Disadvantages
Encourage CRAs to consider disaster vulnerability.	Encourages CRAs to consider financial preparedness for disasters in their assessments of communities' creditworthiness.	Creates incentives for sound financial risk-management practices; is relatively inexpensive	CRAs may conclude that credit ratings do not require revision, given the existence of the FEMA backstop
Raise state and local awareness of risk.	Requires communities to identify major gaps and vulnerabilities and evaluate economic impacts of disasters	Increases awareness of vulnerabilities and creates a sense of ownership; helps the private sector develop solutions	Might not result in any changes in risk-management practices; might require technical and financial support from FEMA
Require state and local governments to cover the first layer of loss.	Requires communities to obtain coverage up to the 1-in-100 or 1-in-200-year event	Federal government no longer covers the first layer of loss but is still there for large, hard-to-insure incidents; removes discussions about amount of self-insurance; improves community incentives to	Makes disagreements likely on the appropriate level of insurance; could make costs burdensome for some communities

Option	Description	Advantages	Disadvantages
		insure against and mitigate risk	
Eliminate PA for BCVE.	Ends the eligibility of public buildings and their contents for the PA program	Federal government no longer covers the first layer of loss. No need to specify what part of loss distribution should be covered by the federal government; removes discussions about amount of self-insurance; creates incentives to insure and mitigate risk	Because communities responsible for large risks are difficult to insure in the private market, might not result in changes in risk-management practices if state and local governments do not view program elimination as politically sustainable

Each of these policy alternatives would result in a different allocation of risk between federal, state, and local governments. Policymakers should consider the advantages and disadvantages of different approaches and consider what point on the risk allocation spectrum makes the most sense to target. There are drawbacks to shifting the entire risk for BCVE to state and local government, but there are also drawbacks of the current approach—in which the federal government frequently covers the first layer of loss and provides assistance for a substantial portion of overall loss.

5. Conclusion and Further Research

As the debate about how to best allocate risk between federal, state, and local governments continues, understanding the financial risk-management practices of state and local governments will be critical. Our research offers a first step in this direction—detailing insurance practices state and local governments employ for their BCVE, the role FEMA assistance plays in these decisions, and options for closing the insurance gap for BCVE. Throughout the course of our work, we identified several areas for additional research that would help further our understanding of state and local government insurance practices and how to encourage communities to purchase insurance:

- **Evaluate the insurance practices of large jurisdictions.** One of our most-striking findings is that large jurisdictions—which are thought to have more resources—tend to have less insurance than midsized ones. However, more work is needed to confirm this conclusion. For example, it is possible that the relationship between insurance share and jurisdiction size could be exaggerated if larger jurisdictions avoid submitting claims for damaged facilities that they can cover with insurance or other sources of funds more

often than smaller jurisdictions. Further work, such as through surveys, is also needed to understand what other types of risk-management strategies large entities use.

- **Evaluate flood insurance practices outside SFHAs.** Our analysis provides some evidence that insurance share for flood damage is lower outside SFHAs, but additional work to support this finding is necessary. Data limitations allowed us to construct only rough measures of the share of repair costs that were outside SFHAs and of the share of damage that was flood related.
- **Analyze the relationship between the purchase of insurance and past disaster frequency.** Although our work found that the frequency of past disaster declarations appears to affect insurance share, more research is needed in this area. Our measure for capturing past disasters, for example, did not distinguish type of peril causing the past disaster or whether a damaged facility received PA in a prior event—factors that might affect insurance purchasing decisions.
- **Analyze the relationship between the purchase of insurance and past disaster frequency.** Although our work found that the frequency of past disaster declarations appears to affect insurance share, more research is needed in this area. Our measure for capturing past disasters, for example, did not distinguish type of peril causing the past disaster or whether a damaged facility received PA in a prior event—factors that might affect insurance purchasing decisions.
- **Evaluate insurance share by property type.** Characterizing the different types of property in a PA application proved difficult. Even in instances in which a facility description indicated that its repair costs were for a building or vehicle, the facility could also include repair costs for other property types. Additional work is needed that explores how insurance share varies by the type of property damaged.
- **Assess the relationship between mitigation funding and insurance share.** Our work could easily be extended to examine the relationship between FEMA mitigation funding and insurance share. Such an analysis, for example, could evaluate whether mitigation funding is higher when insurance share is lower—to assess whether applicants are more likely to mitigate when they are underinsured.
- **Analyze other PA categories of permanent work.** Our analysis focused solely on category E—the category of permanent work receiving the largest percentage of PA funding and the one for which insurance is most readily available. Expanding this analysis to include the other categories would provide insight into state and local government insurance practices for other types of facilities and steps that could be taken to encourage the purchase of insurance for them.

- **Evaluate approaches for facilitating the transfer of risk.** Should responsibility for addressing natural disaster losses shift more significantly to state and local government, they will face the challenge of finding insurance coverage for large incidents. The Terrorism Risk Insurance Act (TRIA) offers a potential model for addressing this challenge.[95] Through TRIA, the federal government essentially provides a backstop for the private insurance market, stepping in to cover losses once a threshold has been reached. Evaluating approaches such as these will help identify innovative ways to close the insurance gap.

6. Key Themes, Questions, and Additional Readings

6.1 Key Themes

- The role of risk management in the public sector
- Transferring risk to the private sector
- Increasing financial preparedness
- Closing the insurance gap
- Improving disaster assistance programs

6.2 Discussion Questions

- What factors should decisionmakers keep in mind when considering the proper allocation of risk between different levels of government?
- What trade-offs should decisionmakers consider when transferring risk to the private sector?
- What options for encouraging state and local government to purchase insurance are most likely to be successful? Why?

6.3 Additional Readings

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Section 5

Future Proofing Society from Flood

The accelerating convergence of climate change, urbanization, and technological disruption is transforming the terrain of flood risk. Disasters once considered rare are now recurring with increasing intensity and complexity often compounding with cascading failures across infrastructure, public health, and cyber systems. In this volatile context, the final section of this volume looks forward, challenging readers to envision what it will take to build a more *adaptive, equitable, and anticipatory flood risk management system.*

Section 5 offers not just a conclusion, but a roadmap charting how science, policy, and innovation must converge to address the compound hazards and structural inequities that define the future of resilience. At the core of section 5 is a recognition that current flood risk systems, though improved by decades of investment, remain constrained by legacy data structures, siloed modeling tools, and rigid regulatory frameworks. These limitations undermine our collective ability to forecast, prepare for, and respond to the cascading nature of modern disasters.

The section opens with a critique of *contemporary flood modeling practices*, calling for rigorous, transparent, and institutionalized frameworks for model validation. More than technical exercise, this is a matter of public trust. Models under gird critical decisions in zoning, insurance, infrastructure design, and emergency response. If those models are flawed—or fail to reflect evolving realities—they leave communities exposed and decision-makers ill-equipped to act with confidence.

Building on this foundation, the next chapters examine the *data systems that must support a more resilient future.* Authors advocate for interoperable platforms, shared metadata standards, and open data ecosystems that enable real-time intelligence across jurisdictions and sectors. These systems are essential to powering everything from risk communication to insurance pricing, from disaster simulations to recovery planning. Flood resilience in the future will depend not only on what data we collect, but how seamlessly and ethically it flows.

This vision is matched by an exploration of *technological innovation*, ranging from advanced floodproofing standards and smart infrastructure to digital twins, sensor networks, and cloud-based analytics. But the section resists the temptation to treat technology as a panacea. Instead, it insists on coupling technical progress with *social equity* asking not only what works, but for whom. One chapter focuses explicitly on

equity data: mapping disparities in investment, access, and outcomes that continue to leave marginalized communities more vulnerable to disaster and more isolated in recovery.

Innovation, the authors argue, must be *participatory*. The final chapter exemplifies this ethos, introducing models of co-developed resilience tools shaped through local engagement, lived experience, and iterative design. Here, research and policy are not imposed—they are negotiated, adapted, and grounded in the everyday realities of those most affected by flood risk. This approach marks a paradigm shift: from top-down interventions to community-centered innovation; from reactive adaptation to *proactive transformation.*

Taken together, the chapters in Section 5 reframe resilience not just as a technical challenge, but as a *societal value.* One that demands persistent investment, cross-sector collaboration, and a readiness to abandon outdated assumptions. Future-proofing our nation's flood resilience will require not only better tools and models, but better relationships: between science and society, policy and people, infrastructure and equity. It will require centering *human experience* at the core of disaster preparedness and climate adaptation.

This final section leaves readers with a powerful imperative: that resilience is not a static endpoint, but an evolving commitment that must be built, rebuilt, and sustained in the face of an uncertain future.

Evaluating and Assessing Flood Models[96]

Sandra K. Knight[97]

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Abstract

The initial purpose of this study was to explore the best strategies in evaluating numerical models and data particularly related to hydroanalytic information. The flood modeling community of practice has not converged on a standard set of technical processes or methodologies nor institutionalized methodologies. The viability and credibility of hydroanalytic models, data, and applications needed to address the complex issues facing us in a changing climate have not been adequately evaluated nor assessed through a common framework. This type of approach requires a paradigm shift within the flood modeling community of practice. It also requires identifying the technical requirements to assure models are valid and accurate for their intended purpose. A more abstract aspect but essential element of institutionalizing best practices, fundamentally begins with leadership and an institutional culture that embraces collaboration, demands excellence, attracts talented and diverse people and values customer perspective. Technical aspects of this nature cannot be created in a vacuum. Acceptance or buy-in of modeling tools and data by a client or end-user relies on engagement early and often and transparency. The institutional guidance - policies/governance/business processes/human resources- must establish clear and authoritative directives, be built on a robust evaluation framework that streamlines functions and embraces a culture of change and innovation.

Keywords

Hydroanalytic information, ensemble modeling, probabilistic risk

1. Making the Case for Evaluation[98]

[96] This compressed paper focusing on flood modeling is extracted from material in the previously published report, The Case for Evaluating Hydroanalytic Information.

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[98] Evaluation is defined in this paper as any criteria, process or methodology that reviews and documents the quality and performance of software, data and models.

"All models are wrong, but some are useful." (Box 1976)[99]

The viability and credibility of the flood models, data, and applications needed to address the complex flooding issues facing the globe in a changing climate requires a paradigm shift within the modeling community of practice (CoP). Currently, there are hundreds of flood models and data systems that inform critical decisions made by federal, state and local governments, public sector, businesses and individuals. These analytical tools are used to plan for capital investments in gray and green water infrastructure, to improve operational activities, to recover and mitigate the impacts from major hydro-climatic events such as floods and hurricanes, and to prepare individuals and communities to be more resilient to flood. Yet, the community of flood developers, modelers and users has not harmonized and/or converged on a standard set of technical processes or methodologies to evaluate and assess the quality and performance of these tools to meet a user's specific needs.

The urgency of an evaluation framework, in part, is driven by the revolutionary changes that are testing the efficacy of existing flood analytics ability to stretch beyond the standard applications in hydrometeorology, hydrology, hydraulics, sediment transport, coastal circulation, wave dynamics, and groundwater. Aging and inadequate infrastructure, population dynamics and development, and escalating flood events, both acute and chronic, caused by climate change, represent at least three grand challenges that will continue to apply pressure to or overwhelm the current state-of-practice in flood modeling. Compounding these challenges are sociopolitical pressures, cyber-security and the general acceptance of evidence-based science. To address some of these tough problems, next generation flood analytics should:

- Integrate and include non-traditional data/models (i.e. remote sensing, social media, market data, ecology, behavioral sciences)
- Assimilate with leading-edge methodologies (i.e. artificial intelligence, deep learning, neural networks, agent-based models, coupled probabilistic and physics-based methods)
- Embrace transformational technologies (i.e. blockchain, micro-processors, drones, sensor technologies, high- performance, cloud and quantum computing)
- Represent complex processes (i.e. coupling of interdisciplinary models, compound flooding, regional/continental scale models, non-stationarity and advances in scientific understanding of natural processes).

To stay competitive and maintain credibility, organizations must be prepared not only to modernize the technical challenges associated with these grand challenges, but also move forward to modernize their institutional strategies to compete in a global marketplace. While committing to quality science and engineering solutions is

[99] This quote is often attributed to the British statistician George E. P. Box in a 1976 paper. Box, George E. P. (1976), "Science and statistics" (PDF), Journal of the American Statistical Association, 71 (356): 791–799, doi:10.1080/01621459.1976.10480949.

essential, new strategies and approaches must also withstand sociopolitical scrutiny to be accepted and used to generate viable alternatives. National and international hydroanalytic[100] laboratories, agencies, consultants and other contributing institutions will need to update their model and data portfolio and their institutions by incorporating transformational science and technology, embracing transparency, fostering collaborative and transdisciplinary approaches, and measuring their progress through a robust evaluation framework.

Flood modelers and data providers naturally strive to build products of high quality that are relevant and reflect favorably upon their credibility. Considerable time and effort goes into the evolution of existing models to reduce and quantify uncertainties, whether as improvements to computational accuracy or by updating physical attributes. New transformational breakthroughs in sensor technologies and big data analytics are disrupting the evolutionary pace of improvements and finding their way into mainstream flood modeling. These breakthroughs could revolutionize the way the community of practice considers flood analytics. In some cases, these approaches are moving so fast that they are replacing and/or leapfrogging the more traditional approaches to flood modeling. Yet, keeping up and incorporating these transformational approaches can be difficult with fixed or fluctuating budgets, leading to compromising tradeoffs between fast delivery of results, lower costs and/or improved quality. To better merge the traditional and the transformative with less compromise, a more harmonized approach to assess and evaluate successes and failure of next-generation products could:

- Quantify the accuracy and uncertainty of updated traditional modeling approaches, alternative or breakthrough analytics and/or hybrid approaches by comparing approaches to established benchmarks or baseline conditions. They might compare outputs such as velocity, flow, wave heights, state, etc. or computational speed and cost.
- Establish the level of uncertainty needed to better match the level of complexity to required use. When is good, good enough?
- Inform investment strategies in data collection, analytics, software, hardware, etc. that are needed to best address end-user decisions.

Evaluating and standardizing the technical requirements to meet the grand challenges are sufficiently complex that it will require a talented pool of modelers and dedicated research and development. But the technical requirements for the next-generation models alone will not suffice and should include institutional guidance and the end-user. Acceptance or buy-in of modeling tools and data by the client or end-user requires their engagement early and often and a transparent framework for sharing. The institutional guidance - policies/governance/business processes/human resources- must establish clear and authoritative directives, be built on an organizational framework that streamlines functions and by organizations that

[100] Hydroanalytic is defined broadly in this paper as any analytic data and models that involve water-related processes.

embrace a culture of change and innovation.

This paper makes a case to the flood modeling community to act now in creating and institutionalizing an evaluation framework. It provides some building blocks for this framework, a synthesis of best practices and next steps to consider. The foundational evaluation framework equally considers technical requirements, user engagement and institutional guidance.

2. The Evaluation Framework Stool

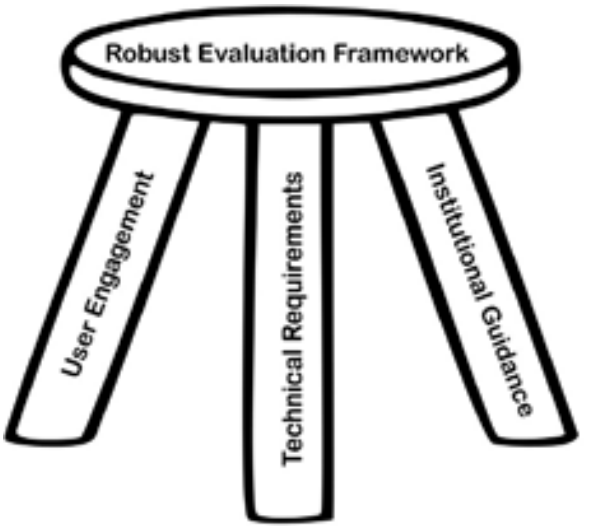


Fig. 1: *The evaluation framework stool*

The evaluation framework stool developed for this study captures three foundational areas that were considered important to the long-term viability and sustainability of hydroanalytic tools. Beginning early and continuing throughout the development of the modeling tools, users help to identify functional requirements and assure better acceptance and transition of the product. Technical requirements for evaluation should include software and data management, qualitative and quantitative criteria and overall quality and performance of the information. Policies, governance, business processes and human resources are part of the building blocks needed to establish the guidance to institutionalize an evaluation framework.

3. User Engagement

Knowing the customer and their needs is a tenet of success in building any product. It is no different in the development of flood analytic tools. It is important to explore the functional needs of the user, the fitness-of-use of the model to their problem and the acceptance of the tool into their operational paradigm. This means understanding

the capacity and capability of the user or their organizations to make best use of the model or its projections.

3.1 Who is using the model and for what use?

The US Army Corp of Engineers (USACE) has been and is a major developer of widely used hydrologic, hydraulic and coastal models. The fact that Corps models, HEC-HMS, HEC-RAS, ADCIRC, STWAVE and others, are accepted by many users provides credibility to the Corps and is a positive indication of the overall quality of their products and acceptance by the community of practice. The technical validation of the Corps software and investments in the management and modernization of the Corps portfolio of models is largely based on internal policy and guidance for a specific modeling software or suite of models that aligns to the direct application of the product(s) to the planning and/or engineering of Corps projects (USACE June 11, 2011).

The acceptance and use of agency models, such as those developed the Corps, by others makes it important to rigorously evaluate and periodically re-evaluate these models for their fitness-of-use and the quantification of technical certainty. This is particularly critical as they may be used in applications outside the purpose for which they were intended and/or by modelers who may not be trained in or understand their use. One major Corps external user, FEMA, lists Corps models as acceptable for use by FEMA contractors, local communities and other agencies that conduct flood insurance studies and prepare regulatory mapping products. This has enormous implications for the over 21,000 National Flood Insurance Program communities that rely on these maps to manage their high-risk flood areas (FEMA 2018). Since FEMA does not develop or manage these models, continued, and expanded partnerships between the client, FEMA, and the developer, Corps, are vital to assure that the models are continually updated, managed and evaluated for fitness-of-use. This is more relevant now than ever as the efficacy of the methodologies that have traditionally quantified flood risk are being tested by the non-stationarity of a changing climate.

3.2 Building it together

Whether informal or formal, communications between the modeling provider and the customer were considered a high priority by many successful organizations. One more formal process was described by leaders at Deltares[101] as they built a digital twin for an operational flood control structure with their client, the Rijkwaterstaat, the agency for water management in the Netherlands. Using a process they call Development, Testing, Acceptance and Production (DTAP), the diagram below clearly articulates the role of both client and supplier at various touch points in the development and delivery of the product. While engagement can result in extra time up front, it streamlines the acceptance of the product as it goes into production. (de Jong, martijn 2018)

[101] Based on conversations between author and lead engineers at Deltares, November 30, 2018.

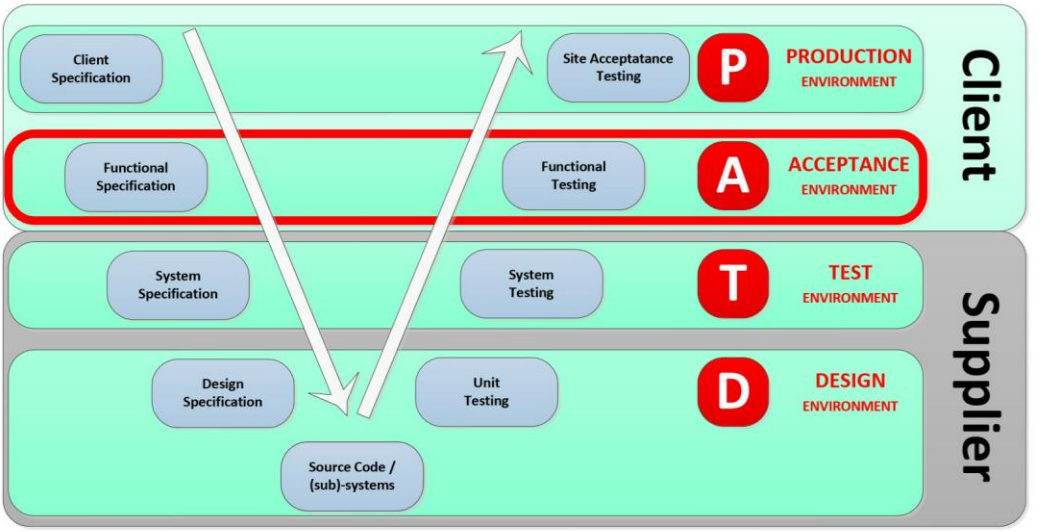


Fig. 2: *Concept model of client acceptance shared with permission by Delatares (de Jong 2018)*

4. Technical Requirements

4.1 The unknowns

George Box, a statistician, famously said in 1976, "all models are wrong, some are useful." (Wikipedia.org/wiki/George Box). Statisticians and probabilistic specialist often describe uncertainty as either aleatory or epistemic. Aleatory, or stochastic uncertainty, relates to the natural or inherent variation of parameters or physical conditions (Fox and Ukumen 2011). Much of the work in flood modeling is based on understanding and quantifying the stochastic variations associated with physical processes or by reducing computational errors. However, with the non-stationarity of atmospheric and hydrologic conditions due to climate change, modelers are now faced with epistemic uncertainty, or imperfect knowledge, requiring more advanced methods in uncertainty quantification. Further, whether aleatory or epistemic, errors can propagate in the modeling chain, or when coupled or integrated with less accurate models (say the coupling of hydraulics with geomorphology or ecology), the outputs can be misleading and imply accuracy that cannot be supported. Implementing an evaluation and assessment process can help mitigate those uncertainties.

4.2 What technical details should you consider?

Software and data management. As new analytic techniques become more mainstream, organizations are moving toward open source and easy accessibility to software and data.

In the spirit of open-source access, Deltares adheres to the mantra "Dare to Share." Others such as the National Weather Service shares codes on products such as WRG-

hydro and the National Water Model[102]. Sharing codes and algorithms among advanced researchers opens the door to transparency and transdisciplinary approaches to solve next-generation problems. Preferences for code languages and data standards were largely heterogenous across the modeling community with minimal attention on data quality. This is an area for improvement in the flood CoP.

Keeping, archiving, or sun-setting data and models is a critical component to modernizing hydroanalytic information. While resource intensive, data management can save money in the long run by eliminating redundant data collection or costly modeling runs. Additionally, curated data provides an essential source of information for ML/AI analytics. The American Meteorological Society makes a case for a standard set of principles due to the growing complexity and increasing volume of observations and model data (Bulletin of the American Meteorological Society, BAM 2019).

Qualitative criteria. There is a heavy reliance on qualitative assessments in selecting and using models. Qualitative criteria provide the basis for the USACE hydrology, hydraulic and coastal community of practice (HH&C CoP) portfolio of over 70 tools, data, and models (USACE June 11, 2011). Common criteria used by the Corps include software and data accessibility, graphical user interfaces and visualization, documentation, training, and technical support. FEMA also requires product providers to meet certain guidelines and standards, but at the end-of-the-day, the acceptance of a computer program for H&H analysis is driven by the US Code of Federal Regulations,44CFR 65.6 (a)(6), which requires computer programs used to perform hydrologic or hydraulic analysis must be reviewed and accepted by a government agency, be well documented and generally available for current and future use (US Code of Federal Regulations 2009). Across the organizations reviewed, tools and models that were peer-reviewed along with the experience of the modeler were qualitative criteria that added credibility and improved acceptance of the model and its outputs. Fitness-of-use was a consideration, but acceptable levels of accuracy were often not specified. Further, physics- or process-based methodologies were generally deemed better approaches more often than data-driven results because of the acceptance of the science behind the modeling approach.

Quantitative criteria. There are many good practices for using quantitative criteria and techniques, particularly when testing the validity of the software or the accuracy of the results. Benchmark testing, test beds, uncertainty quantification, sensitivity and statistical analysis and product scoring represent some of the more accepted practices. Test beds can provide high quality observational and experimental data that are critical for developing, verifying and validating algorithms and models. Evidence-based processes such as benchmarking are helpful to identify gaps or errors in the model, make adjustments and evaluate relative capabilities among different models, but do not absolutely quantify uncertainty. Sensitivity analysis -varying boundary

[102] Based on conversations with various experts at Deltares and at the National Weather Service.

conditions, grid size, time steps or inputs like manning's n- is another approach to identify potential sources of uncertainty in modeling data and helping to set the boundaries for the outcomes.

Flood model developers and users have long used benchmarking to better understand the ability of their tools to replicate nature. USACE Hydrologic Engineering Center completed a verification and validation study of their widely used hydraulic models, HEC-RAS 1D and HEC RAS -2D unsteady flow models. They first verified the models could reproduce known analytical solutions from simple to complex and then validated them to real world data sets (Brunner 2018). In the first step, initial parameters such as friction, many need calibrated. Once calibrated to the known solution (verification) and validated with real data, these models are then used for predictions. The Coastal and Hydraulics Laboratory followed a similar evaluation approach for its Coastal Modeling System but expanded their testing to include many laboratory and field data sets (Demirbilek and Rosati 2011). The CHL's research facility at Duck, NC excels at collecting coastal observations for validating models and algorithms and has automated evaluation of coastal numerical models (Bak 2018). HR Wallingford applied benchmark tests to a suite of 1D and 2D hydraulic models. They conducted tests for numerical accuracy and software capability (verification) and reproducibility (validation) (Neelz 2013). While similar in approaches, there are no universal sets of bench tests that are shared among developers and used across the different flood models.

Meanwhile, more sophisticated approaches are making their way into flood modeling practice. These include Verification, Validation, and Uncertainty Quantification (VVUQ), probabilistic risk assessments (PRA), and ensemble modeling. More will be discussed on these approaches below.

Performance – combining qualitative and quantitative. Often a combination of qualitative and quantitative criteria, standards and expert elicitation are applied to evaluate the quality and best use of individual models and/or to assess a portfolio of modeling products. A hybrid approach for assessing models can be used to rate or score their ability to meet the client requirements. The benchmarking testing for HR Wallingford, above, tested the ability of 13 models to perform under various qualitative and quantitative criteria or scenarios. There were no winners or losers, just results that allowed the end-user to choose which product was better for say, large basin-scale inundation or dam failure impacts (Neelz 2013). In a similar type of analysis. FEMA contracted with Compass Production and Testing Services Joint Venture to review 26 H&H models for their storm rapid forecasting capability to improve emergency preparedness and response. The assessment was based on a weighted review of ten evaluation factors and rated on a scale of 1 (least desired option) to 5 (best option). A more objective statistical analysis of the top three models then compared the difference in computed and observed water elevations. (COMPASS 2019). Another approach taken in the UK was designed to inform their Long-Term Investment Scenarios. They used a National Flood Risk Assessment (NaFRA) framework to quantify uncertainty of a large portfolio of both local and national flood assessments

(Sayers 2011). FEMA has taken a more qualitative approach to inform their portfolio of investments in flood hazard studies. They have a Coordinated Needs Management Strategy (CNMS) that tracks if the flood maps in approximately 22, 0000 communities have New, Validated, or Updated Engineering (NVUE) stream miles.

5. Institutional Guidance

As observed in this study, successful modeling and analytic organizations have a well-defined institutional infrastructure. That is, they seek out good leaders, clearly articulate and enforce policies and procedures, embrace a culture of evaluation, exhibit strong business acumen and most importantly, hire and retain qualified and enthusiastic people. Some examples are described here.

Good data standards and practices often are the result of good policies. The US government enacted the Foundations for Evidence-Based Policymaking Act (or OPEN Government data Act (US Public Law 115-435), made data open and machine-readable format (US Public Law 2018). The National Oceanic and Atmospheric Administration has long practiced an open data policy and has established detailed policy requirements for data standards and accessibility of environmental data (NOAA 2007).

Many organizations embrace evaluation using internal tools, such as annual reporting or Quality Assurance/Quality Control processes, and external practices, such as special advisory boards and laboratory reviews. FEMA's Technical Mapping Advisory Council provides guidance to FEMA on their floodplain mapping products including recommendations for enhanced quality assurance and control (FEMA 2016). Likewise, the USACE Coastal Engineering Research Board and Environmental Research Board, provide recommendations that help guide and inform the future of the US Engineer Research and Development Center modeling activities. All three of these committees are established under the Federal Advisory Committee Act[103])

To financially manage and sustain a modeling and data portfolio, organizations should use good business processes. Life-cycle asset management practices, one of those good business processes, goes beyond managing just physical infrastructure to managing modeling assets. These assets- software, data, hardware and people- are particularly important as they often drive the fundamental decisions of an organization such as investments in Corps water infrastructure projects or execution of programs like the National Flood Insurance Program. Water infrastructure real property, observational platforms and flood management software are all assets that benefit from a life-cycle strategy that plans for capital improvement, maintenance, replacement and disposal. Further, to meet rapidly changing economic, environmental and socio-political challenges, organizations must be well structured and have business processes that keep them agile and able to adapt to technological change.

[103] The Federal Advisory Committee Act of 1972 provides the legal foundation for how federal advisory committees operate.

6. Building the framework

6.1 The Model Evaluation Cycle

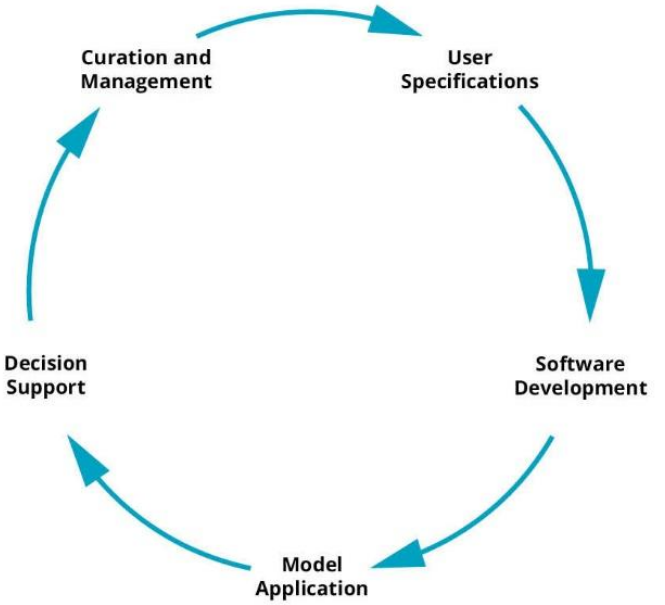


Fig. 3: *The modeling evaluation cycle. Phases to consider in development of an evaluation framework.*

The simplified cyclical diagram in Figure 3 coupled with examples in Table 1, identify a series of steps from conception to development to use and curation. The cycle can provide a roadmap to select and establish evaluation methodologies in each phase in context of the user, the technical requirements and the institutional practices. To ensure quality control, responsibilities should be assigned to the product developer, modeler and/or application user and end-user. Table 2 provides some examples.

Table 1. Examples of good practices in each step of the model cycle. The letters in parentheses align to each leg of the stool: U-User, T-Technical, I-Institutional

USER SPECS	SOFTWARE DEVELOPMENT	MODEL APPLICATION	DECISION SUPPORT	CURATION AND MANAGEMENT
• Acceptance (U) • Speed (T) • Accuracy (U) • User Capacity (U) • Adheres to Laws (I) • Fitness-of-use (T,U) • Ease-of-use (T)	• SCRUM (U,T) • Test Beds (U) • Version Control (I) • Open Source (I) • Peer Review (T)	• VVUQ (T) • Benchmark (T) • Data Standards (T) • Model Performance (T,U) • Skill Score (T) • Accuracy (T,U)	• Visualization (U) • Understandable (U) • Timeliness (U) • Credibility (T) • Operational Acceptance (I) • Confidence in Results (T,U)	• Documentation (I,T) • Standards (T) • Accessibility (U,T)

Table 2. Sample Quality Responsibility Chart

PRODUCT DEVELOPER	MODELER / APPLICATION USER	END-USER
• Applies necessary Quantitative measures (VVUQ, Benchmarking, test beds, skill scores, computational performance, etc) • Applies Qualitative measures (documentation, user's manual, accessibility, tech support, peer review, use cases) • Engages end-user in development of new software applications • Provides proof of passing required Certification Process • Software curation/version control	• Demonstrates experience using model-use cases • Has proper accessibility and ability to use required Computer Platform • Has Modeling Credentials • Has Education/training appropriate to problem area • Assures technical requirements are satisfied • Manages Data quality and model execution • Captures data and model uncertainties • Curates study applications and data inputs/outputs	• Sets the Acquisition Specs • Accepts end-products and results • Assures Quality is meeting expectations • Manages Quality of Product(s) within Portfolio • Assures Fitness-of-Use (reviews certifications, use-cases and quality) • Sets Performance Standards • Applies results with understanding of limitations and uncertainties • Curates and manages enterprise product data

7. Portfolio Assessment

While technical criteria can be used to assess the quality of model data, it may not provide the information needed to influence sociocultural, environmental or economic decisions. Using a portfolio strategy, similar to the CNMS or NaFra above, a suite of model and data assets could be scored according to their ability to consider other important parameters such as community vulnerability, climate change, and/or economic development. Having a robust portfolio of diverse tools gives the flood risk manager or policy decision maker the information he/she needs to determine where priority studies may be needed, what geographic areas warrant closer scrutiny due to higher future risks or at-risk populations, or where more research is needed to reduce uncertainty. Some conceptual ideas on portfolio scoring can be found in the main report (Knight 2021).

8. Certification of Modelers and Models

During this study, professionals who both developed and used models expressed their concerns that the quality of modeling results, regardless of the model, were

explicitly tied to the capability and proficiency of the modeler. Many organizations such as USACE Hydrologic Engineering Center (HEC) and American Society of Civil Engineers (ASCE) provide training and support for specific H&H models, but that training is not a requirement for use. Other organizations support users of their software through fairs, bootcamps and training. These events not only help the users improve their own skills but contribute to improvements to the software and can result in unsolicited positive testimonials of the product. There are many technical and professional organizations that award certifications to codify an individual's credentials. Examples include the Certified Floodplain Manager by the Association of State Floodplain Managers (ASFPM) or the Diplomate Water Resource Engineer by the American Academy of Water Resource Engineers (AAWRE). However, this study did not find evidence of any certification or any certifying organization for hydroanalytic modeling professionals. This may be in part due to the difficulty in developing a process that would accommodate the highly variable array of models and variable level of skills needed to apply them.

As with the credentialling of professionals who apply flood model tools, there was no evidence of third-party organizations that certify flood or H&H software. The reality of doing so is complicated by the various requirements of end use and the lack of standards. USACE self-certifies its own models for the specific functional categories of planning, engineering, and operations. Yet, FEMA accepts these models and uses them for flood insurance rate maps. In the absence of set standards or certifying organizations for modeling and data products, a tiered approach could be taken to align models and data to the best or most appropriate use. Table 3 is a modification to an approach used by the USACE (USACE June 2011). The nomenclature follows USACE guidance where *enterprise* software is mandated or required by the agency, *preferred* is software used by a specific community of practice and *allowed* is niche software good enough for a specific use. The tiers refer to the levels of review required, Level 1 being extensive to Tier 3, moderate.

Table 3. Proposed tiered approach to hydroanalytic software quality review.

LEVEL OF REVIEW	MODEL COMPLEXITY	USE (ENTERPRISE, PREFERRED, ALLOWED, SINGLE USE OR NICHE)	PROCESS FOR EVALUATION
Tier 1 (Extensive)	Highly complex software, software containing new analytical approaches and not previously certified	Mandated or enterprise level software	Third party certification based on qualitative and quantitative criteria
Tier 2 (Moderate)	New algorithms or major update to currently acceptable complex models	Models generally preferred or recommended for use by agency or previously certified	Expert elicitation with review of existing certifications and review of modifications and peer reviewed publications
Tier 3 (Minor)	Standard or previously certified models with minor revisions or expired certifications	Enterprise, Preferred or Allowed	Internal expert review based on documentation

9. What's New and Emerging?

The hydroanalytic community of practice has not been idle when considering new

and emerging technical approaches. AI/ML analytics are being merged or integrated with process-based approaches in areas such as the energy-water nexus to quantify uncertainty and make analysis quicker (Zaidi et al. 2018). And hybrid approaches in flood analysis and prediction using ML methods, data decomposition techniques and ensemble approaches have been shown to improve predictions according to different study by Mosavi et al. (Mosavi et al. 2018). More intense efforts are being employed to quantify and reduce uncertainty using Probabilistic Risk Assessments (PRA) and Verification and Validation and Uncertainty Quantification (VVUQ). Meanwhile continental scale modeling is pushing the limits of flood modeling to something that was unimaginable just a few years ago.

Ensemble Modeling. Ensemble modeling, long used in weather and climate forecasting is gaining traction in hydrology, river forecasting and coastal models. According to Wang et al., ensemble simulations of hydrologic models can use an ensemble of input data; assemble different process approaches for each part of the hydrologic cycle; or select and use multiple models to compare outputs (Wang et al 2021) The NWS Hurricane Prediction Center typically builds a consensus model of an ensemble of the "average" track of the outputs of the top six global hurricane prediction models (Masters 2019). The Hydrologic Ensemble Forecast Service (HEFS) developed NWS for river forecasting centers, ingests downscaled climatologic and weather data while adjusting for bias and calculating uncertainty to create an ensemble flow forecast. The significance of the HEFS lies in its ability to quantity uncertainty using an ensemble approach while also reducing the subjective nature of riverine forecasts (Wells 2018).

Probabilistic Risk Assessment. Moving from deterministic approaches to probabilistic risk assessments (PRA), Monte Carlo analysis and Baysian approaches is a way to look at the probability of plausible outcomes over a range of parameter estimates. The use of these approaches helps communicate and identify uncertainty. PRA is moving mainstream in flood hazard assessments by the Nuclear Regulatory Commission, FEMA, the UK Environmental Agency and others. Even with PRA, the overall results are influenced by variations in input parameters, such as Manning's n for hydraulic models, sources and level of accuracy of information, such as elevation data, or even algorithm selection, such as depth-damage curves. Numerous scholarly papers and studies have been conducted to demonstrate the usefulness of these techniques to identify the dominant sources of uncertainty based on variable model assumptions and data sources.

Verification and Validation and Uncertainty Quantification, VVUQ. VVUQ takes benchmarking to a more complex level that leads to uncertainty quantification. The American Society of mechanical Engineers has a special journal and a standards committee for VVUQ. The definitions, below, by ASME for VVUQ were meant to focus on machine learning and computational fluid dynamics but are similar to how V&V are defined in hydraulic modeling.

- *Verification is performed to determine if the computational model fits the mathematical description.*

- *Validation is implemented to determine if the model accurately represents the real-world application.*
- *Uncertainty quantification is conducted to determine how variations in the numerical and physical parameters affect simulation outcomes. (ASME no date).*

Likewise, the National Academies of Sciences examined best practices and scientific gaps using VVUQ in large-scale computational simulations of physical processes. The quantities of interest (QOI) that represent physical processes must be identified and the VVUQ designed to characterize the differences between computed QOIs and true QOIs. In hydrodynamic models or flood models this usually means water surface elevation, velocity, discharge, or wave height. Quantification may reveal that a model is excellent for on QOI but poor for others (National Research Council 2012).

Continental Scale Modeling. Continental or large regional scale models can help provide a bigger picture of flood threats and inform water resource managers, first responders, communities, individuals, and others prepare and manage flood risk. With flooding often concurring simultaneously in many places at once and/or over large geographic regions, the ability to rapidly predict and forecast the timing and intensity of these events is needed to better prepare and respond. The NWS with its partners is working to fill that gap with the National Water Model. The model represents multiple physical processes across the entire country, transforming water information services and streamflow forecasting. Using meteorological data making best use of gages and radar precipitation observations, the model produces hourly simulations for 2.7 million stream reaches. This near real-time analysis of stream flow and other surface and near-surface hydrologic information can provide short range (hourly to 18 hours), medium range (four times daily out to 10 days) and long range (30-day ensemble) forecasts (NOAA no date).

The First Street Foundation[104] is filling another gap, providing a national risk assessment that includes areas of insufficient data and covering fluvial, pluvial and coastal flooding. Using a continental-scale 30meter resolution model, this analysis can augment FEMA flood studies and simulate within reasonable accuracy and at lower cost, flood risk in areas of the country not previously mapped or studied (Wing et al. 2017).

10. Next Steps for Evaluation and Assessment

Consistent standards and evaluation practices are needed to assess hydroanalytic information. The flood analytic community of practice is making great strides in the modernization and improvement of next-generation flood products. This provides an opportunity to get ahead of the curve by codifying existing best practices and incorporating new practices in the management of the software, data and models that support flood information end-users and decision-makers. A more harmonized approach to evaluation and assessment would bring transparency to flood product

[104] https://firststreet.org/

development, embrace lifecycle maintenance, curation, and updates of these products, and would reduce uncertainty in results.

To get started, champions will be needed at all governance levels and across many disciplines in existing professional organizations, government agencies, private industry and academia that understand the importance of building a robust evaluation strategy. Leveraging existing requirements and needs for next-generation tools and capitalizing on the current body of knowledge and practice, the modeling community of practice should convene- whether through special committees, workshops, or conferences- with the goal of generating a suite of best practices that could lead to harmonized processes and approaches. To track progress, organizations should establish detailed and clearly defined metrics for managing performance in each leg of the evaluation stool and/or throughout the modeling cycle. Importantly, the evaluation process must be institutionalized and implemented. Current federal interagency mechanisms could be leveraged to establish a governance platform for broad implementation of flood analytic standards. On a smaller scale, individuals and individual organizations can adopt a culture of evaluation as they build new and/or update or modernize their current portfolio of hydroanalytic tools.

Finally, transparency and a willingness to share intellectual property requires a change in culture that can be difficult within small organizations but gets even harder across large agencies and multi-organizational groups. Historical practices of isolated development and unnecessary competition may take decades to overcome, but changes are forthcoming as a new wave of transdisciplinary innovators joins to collectively improve the state-of-the-practice. Let's not wait disaster to transform the changes needed to implement an evaluation framework.

11. Key Themes, Questions, and Additional Readings

11.1 Key themes

From this research effort, the following themes emerged:

- The viability and credibility of the flood models, data, and applications needed to address the complex flooding issues facing the globe in a changing climate requires a paradigm shift within the modeling community of practice (CoP).
- The urgency of an evaluation framework, in part, is driven by the revolutionary changes that are testing the efficacy of existing flood analytics ability to stretch beyond the standard applications in hydrometeorology, hydrology, hydraulics, sediment transport, coastal circulation, wave dynamics, and groundwater.
- While committing to quality science and engineering solutions is essential, new strategies and approaches must also withstand sociopolitical scrutiny to be accepted and used to generate viable alternatives.

- Flood modelers and data providers naturally strive to build products of high quality that are relevant and reflect favorably upon their credibility.
- The acceptance and use of agency models, such as those developed by the Corps, by others makes it important to rigorously evaluate and periodically re-evaluate these models for their fitness-of-use and the quantification of technical certainty. This is particularly critical as they may be used in applications outside the purpose for which they were intended and/or by modelers who may not be trained in or understand their use.
- A larger number of road and bridge projects completed after Hurricane Floyd (measured as completed with FEMA Public Assistance funding) made communities more resilient than communities with fewer projects completed.

11.2 Discussion questions

- What did statistician, George Box say about models?
- What are three key pillars for a robust evaluation framework for hydroanalytic models?
- What is most of the work in flood modeling based upon?
- What approach have flood modelers long-used to better understand the ability of their model to replicate nature?
- What are some of the most common qualitative and quantitative criteria for evaluating flood models?
- Describe the model evaluation cycle and explain its key components?
- Discuss the role of certification for modelers and models? How might a certification program be achieved for hydroanalytic model that does not suppress innovation?
- What are some of the emerging trends in hydroanalytic modeling?

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Provisioning Better Data for Flood Risk Management

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Abstract

This chapter explores the transformative role of emerging data technologies in advancing flood risk management in the United States. It highlights how innovations such as IoT flood sensors, satellite-based remote sensing, structured building data, AI-driven flood modeling, and immersive tools like digital twins and augmented reality are reshaping the field. These technologies offer real-time monitoring, granular exposure analysis, and dynamic scenario planning that improve preparedness, response, and resilience. By integrating these tools into decision support systems and ensuring equitable access to data, communities can better anticipate and manage flood risks in a changing climate.

Keywords

Flood analytics, hazard estimates, special flood hazard area (SFHA)

1. Introduction: The Data Imperative for Modern Flood Resilience

Flooding is one of the most destructive and costly natural hazards in the United States, affecting millions of people annually and causing billions in damages. Traditional approaches to flood risk management have relied heavily on historical records, static floodplain maps, and siloed datasets. In an era of climate uncertainty, aging infrastructure, and rapid urbanization, such approaches fall short. More frequent extreme rainfall events, sea-level rise, and land use change demand a data-rich, dynamic, and scalable flood risk management framework. The emergence of new technologies—from IoT flood sensors and satellite-derived data to digital twins and artificial intelligence—is reshaping how flood risk is modeled, communicated, and mitigated. This chapter explores how modern data systems and modeling innovations can drive smarter, more resilient flood risk management, with a focus on structured data, real-time sensing, and emerging technologies.

2. IoT Flood Sensors: Real-Time Monitoring at Scale

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The integration of low-cost Internet of Things (IoT) flood sensors into local, regional, and national monitoring networks represents a pivotal advance in flood resilience. Developed through collaborations between DHS Science and Technology Directorate, CREATE, and the Flood Apex Program, these sensors provide granular, real-time data on water levels, rainfall, and soil saturation (CREATE, 2019). Units are modular and can be equipped with cameras, temperature sensors, or barometers depending on site needs. They connect via Wi-Fi or cellular networks to cloud-based platforms and often integrate with local GIS systems, enhancing situational awareness for emergency managers and first responders.

The deployment of these sensors marks a shift from reliance on legacy gauges and infrequent manual measurements to a dynamic, distributed sensing ecosystem. These devices are compact and cost-effective, allowing for dense coverage across vulnerable floodplains, culverts, underpasses, and stormwater systems. Once installed, the sensors transmit data at configurable intervals ranging from minutes to hours, which can be analyzed in real-time or fed directly into modeling platforms for forecast updates.

One of the major strengths of IoT flood sensors is their adaptability to diverse environments. In urban areas, they can be embedded in critical infrastructure corridors or transportation networks to monitor rising water levels that threaten roadways or subways. In rural or coastal settings, they support agricultural decision-making and enable early evacuation notices in regions with limited traditional monitoring infrastructure. Some units also include backup batteries or solar charging capabilities, allowing continued operation during power outages.

Beyond monitoring, IoT sensors provide valuable data inputs for flood forecasting and early warning systems. Their high-resolution temporal data enhances predictive models and improves lead times for emergency response. Cost-benefit analyses show favorable returns, with benefit-cost ratios (BCRs) exceeding 2.7 in several pilot regions due to reduced property losses and improved emergency response times (CREATE, 2019). When deployed strategically in under-resourced or flood-prone areas, these sensors democratize access to timely risk information, particularly when paired with community-based resilience planning.

A leading example of these sensors in action comes from Charlotte-Mecklenburg, North Carolina. Through a partnership with DHS S&T and the Flood Apex Program, Charlotte-Mecklenburg Storm Water Services (CMSWS) deployed over 100 low-cost flood sensors across urban and suburban settings, integrating them into the county's Flood Information and Notification System (FINS). The sensors were strategically placed at vulnerable road crossings, sanitary sewer infrastructure, and streambanks, providing near-real-time data that supports automated alerts, road closures, and post-event damage assessments (CMSWS, 2020). Over time, these deployments have enabled CMSWS to monitor 96% of the county's mapped flood risk in real time, transforming its flood situational awareness and mitigation strategy.

The project's success was supported by careful planning, including pre-deployment site selection, cellular connectivity testing, and development of a robust operation and

maintenance framework (CMSWS, 2020). The sensors not only reduced monitoring costs relative to scientific grade gauges but also enabled rapid deployment during flood events and served as decision support tools for infrastructure maintenance and capital investment planning. Their inclusion in community outreach and educational initiatives has also increased public engagement and understanding of flood risk.

Standardization is a growing focus in this space. Efforts by the Association of State Floodplain Managers (ASFPM) and partners have led to the development of ANSI/FM 2510 standards, which guide calibration, accuracy thresholds, data formatting, and communications protocols for flood sensors (ASFPM, 2020). Such standards are critical to ensuring interoperability and long-term data utility across agencies and jurisdictions.

Additionally, integration with platforms such as FEMA's Integrated Public Alert and Warning System (IPAWS) and NOAA's National Water Model enhances coordination. Local jurisdictions can configure alerts to trigger based on sensor thresholds, enabling automated road closures, push notifications, or dynamic signage in flood zones. As sensor technology matures and deployment costs decline, the vision of a national flood sensing grid—interconnected and locally actionable—becomes increasingly feasible.

Ultimately, IoT flood sensors are more than technical devices; they are enablers of adaptive governance. They provide local officials and residents with the information needed to make timely decisions, prepare for rising threats, and reduce vulnerability in real time.

3. Remote Sensing Platforms and Satellite-Derived Flood Data

Flood data acquisition has advanced significantly with the expansion of satellite-based remote sensing platforms. Synthetic Aperture Radar (SAR) sensors aboard satellites such as Sentinel-1 and the upcoming NASA-ISRO Synthetic Aperture Radar (NISAR) mission enable consistent flood detection, even under cloud cover and at night. This is especially important during active storm systems when optical sensors are obstructed by weather conditions. SAR's ability to penetrate cloud layers and capture surface water extent in near real-time makes it a cornerstone for modern flood monitoring efforts.

Optical satellites such as Landsat and MODIS have also been critical in supporting long-term flood trend analysis, land cover classification, and seasonal water variability monitoring. The Surface Water and Ocean Topography (SWOT) satellite, launched in 2022, adds another dimension by mapping global surface water elevation and slope with unprecedented resolution. It enables better quantification of storage and flow across lakes, rivers, and floodplains, providing invaluable hydrologic data for both flood forecasting and water resource management (AAAS, 2023).

One illustrative application is the Observed Flood Extent (OFE) database, which leverages over four decades of Landsat data to build pixel-level flood recurrence maps. These spatially explicit datasets help identify areas with frequent inundation,

informing zoning decisions, infrastructure investments, and insurance modeling (FEMA, 2019). By integrating OFE outputs with real-time remote sensing, emergency managers can quickly assess which neighborhoods are at risk and compare current flood extents to historical baselines.

To move beyond simple flood detection, tools like the Floodwater Depth Estimation Tool (FwDET) have emerged. FwDET calculates water depth by overlaying remotely sensed flood extent polygons onto digital elevation models (DEMs), producing depth estimates without requiring hydrodynamic simulations. These outputs are critical for estimating damages, prioritizing response, and supporting evacuation planning (Cohen et al., 2017).

Additionally, the widespread availability of Light Detection and Ranging (LIDAR) data has further enhanced flood modeling accuracy. LIDAR-derived elevation datasets offer sub-meter vertical resolution, capturing fine-scale terrain variations essential for understanding overland flow patterns and drainage connectivity (USGS, 2020). LIDAR can detect subtle changes in levees, channel banks, and floodplain microtopography—details often missed in coarser elevation models.

Remote sensing platforms are also becoming more interoperable. Multiple federal agencies—including NASA, NOAA, FEMA, and USGS—are collaborating to align satellite data products with operational tools such as the National Water Model and Risk Mapping, Assessment, and Planning (Risk MAP) program. This allows near real-time satellite observations to be transformed into actionable information, such as flood inundation forecasts and exposure overlays, tailored to local and regional needs.

Emerging commercial constellations of small satellites are beginning to supplement government assets, offering higher temporal resolution and tasking flexibility. These systems can revisit target areas multiple times per day, providing continuous coverage during evolving flood events. In tandem with drone-based and airborne sensors, these data streams enable rapid, multi-angle assessments of infrastructure damage, water levels, and environmental impacts.

Among the most promising commercial platforms is ICEYE, a private constellation of SAR microsatellites capable of capturing high-resolution flood extent and depth data at 3-meter spatial resolution. Unlike traditional SAR platforms, ICEYE delivers daily coherent ground-track repeat imaging, which allows emergency managers to track changing flood conditions nearly in real-time. Recent case studies in Bangkok and Tula de Allende demonstrated ICEYE's ability to provide flood depth maps with a mean absolute error of just 24–32 cm (Nygren et al., 2024). These maps, when paired with population datasets such as the World Settlement Footprint (WSF) and OpenStreetMap building footprints, enable automated flood impact visualizations that can inform first responders and international aid organizations within hours.

Similarly, Interferometric Synthetic Aperture Radar (IFSAR), employed by platforms like Alaska Mapping Initiative and national terrain mapping efforts, contributes to high-resolution elevation models crucial for hydrodynamic modeling in remote regions. While not as dynamic as near-real-time SAR for active monitoring,

IFSAR provides foundational terrain data at broad scales with vertical accuracies suitable for floodplain delineation and infrastructure vulnerability assessments. Integration of IFSAR-derived DEMs with SAR-based flood extent data can significantly improve inundation mapping in data-scarce areas.

Taken together, these innovations in remote sensing mark a significant leap forward in flood risk awareness. By fusing historical context, real-time observations, and predictive modeling, satellite platforms are not only enhancing preparedness and response—they are redefining the spatial and temporal scales at which flood risk can be understood and managed. Flood data acquisition has advanced significantly with the expansion of satellite-based remote sensing platforms.

AIR Worldwide conducted a comparative study of flood hazard estimates for DHS S&T in support of the Flood Apex program. The *Comparative Flood Hazard Estimates Study* found significant inconsistencies between Risk MAP Flood Insurance Rate Maps (FIRMs) and high-resolution datasets derived from remote sensing, including lidar and satellite imagery. The study showed that Risk MAP tended to underpredict flood extents in areas of urban expansion and poorly mapped floodplains. In particular, flood boundaries derived from FATHOM and SSBN models, as well as high-resolution satellite imagery, captured 20–50% more structural exposure than FIRMs in pilot locations like Houston and Baton Rouge. These results indicated a clear need to integrate satellite-derived flood data into the regulatory mapping process, especially where infrastructure development has outpaced map updates (AIR Worldwide, 2019a).

The study also advocated for a blended approach to risk communication—using traditional FIRMs for regulatory purposes while leveraging satellite and sensor-based observations for operational response, community planning, and insurance analytics. This dual strategy allows agencies to maintain compliance while using more dynamic datasets for decision support during and after flood events.

4. Structured Building Data: Enhancing Granularity in Flood Risk Modeling

Accurate modeling of flood exposure depends not only on topography and hydrology but also on the detailed characteristics of the built environment. In past decades, flood risk assessments have often relied on aggregated census data or land use proxies to estimate building exposure. However, such generalized approaches lack the spatial precision and structural specificity required for modern modeling techniques. Recognizing this gap, the release of the USA Structures dataset by Oak Ridge National Laboratory and FEMA represents a transformative advancement. DHS S&T co-funded the original development of the USA structures dataset, the proof-of-concept for the machine learning and extraction methodologies, and baseline set of building structure outlines for an initial set of priority states. This nationwide geospatial database includes more than 125 million individual structures, each enriched with detailed attributes such as address, use type, square footage, height, and footprint geometry (Yang et al., 2024).

The dataset is derived from high-resolution satellite and aerial imagery processed through advanced convolutional neural networks (CNNs). These models detect and delineate building footprints with high spatial fidelity, after which each structure undergoes a robust Verification and Validation Model (VVM) process. This ensures that only verified structures exceeding 450 square feet are included, reducing false positives and maintaining geometric accuracy. Each record is further enriched through spatial conflation with authoritative datasets such as Homeland Infrastructure Foundation-Level Data (HIFLD), Census TIGER shapefiles, LightBox parcel records, and HUD property classifications. This multilayered integration enables the assignment of occupancy types—from single-family dwellings and apartment complexes to schools, fire stations, and hospitals.

Structured building data is critical for advancing a range of flood modeling applications. At the simplest level, building footprints and elevation allow analysts to estimate inundation risk for individual structures. More complex models use this data to calculate exposure metrics, potential damage functions, and cascading impacts to adjacent infrastructure. For example, a flood event that affects a distribution warehouse or medical facility can have far-reaching consequences, even if only a handful of buildings are inundated.

The inclusion of address-level data, centroid coordinates, and zoning categories enables seamless linkage to insurance records, emergency notification systems, and municipal planning tools. In flood-prone jurisdictions, this has allowed local governments to pre-identify at-risk populations, automate damage estimation post-disaster, and prioritize mitigation grants under FEMA's Hazard Mitigation Grant Program (HMGP) or Building Resilient Infrastructure and Communities (BRIC) program.

Additionally, the USA Structures dataset is designed for continual improvement. Regions with persistent cloud cover or low-resolution imagery are slated for iterative updates as better remote sensing data becomes available. Strategic sampling approaches, like ISOSCELES, allow for targeted model retraining to improve performance in challenging environments. The dataset's open and modular architecture supports integration with digital twins, enabling communities to simulate flood impacts in 3D environments with parcel-level resolution.

Structured building data also helps correct longstanding inequities in flood risk mapping and resource allocation. Traditional FEMA Flood Insurance Rate Maps (FIRMs) often omit millions of structures at risk, especially in areas outside the Special Flood Hazard Area (SFHA). By overlaying modeled flood extents from remote sensing with the USA Structures data, analysts have found that national flood exposure may be two to three times greater than previously estimated (Wing et al., 2018). The dataset thus serves as a foundational layer for equitable planning, particularly in disadvantaged or underserved communities.

In sum, high-fidelity structure-level data provides a critical building block for the next generation of flood resilience tools. It underpins everything from local hazard mitigation plans to global catastrophe models, ensuring that both public agencies and

private insurers can plan, respond, and invest with greater precision and fairness.

The *Comparative Flood Hazard Estimates Study* also revealed how inconsistent structure representation on FIRMs led to undercounting exposure in many areas, particularly in fringe flood zones. When overlaid with advanced building inventories like the USA Structures dataset, the contrast in structural exposure was striking. For example, one analysis in Harris County, Texas, showed over 30% more structures exposed to flood hazard zones than depicted on official FEMA maps. These data have since been used to recalibrate loss estimation models and reevaluate risk prioritization under the NFIP.

The study's findings reinforced the importance of granular exposure data for flood analytics. In areas with high redevelopment or infill construction, the addition of recent building footprints changed the calculated average annual loss by more than 40%, highlighting how omissions in existing datasets distort actuarial risk. These insights have driven the development of dynamic exposure databases and prompted FEMA to initiate efforts to supplement FIRMs with structure-specific overlays in high-risk areas (AIR Worldwide, 2019a).

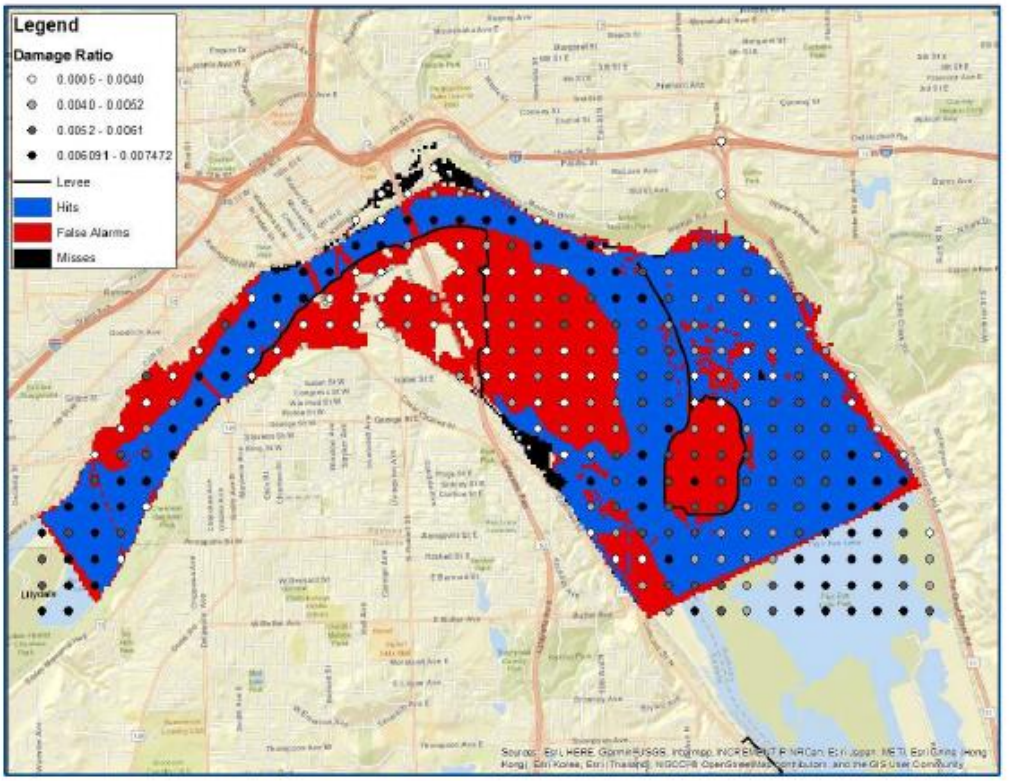


Fig. A: *Benchmark Comparison of Flood Analytic Models*

Results of flood modeling overlaid on USGS benchmark comparison in Minneapolis, MN to show the effect of levees in the AIR Inland Flood Model. Points represent flood vulnerability; lighter points are less vulnerable; darker points are more vulnerable. (Air Worldwide, 2019b)

5. Advances in Flood Risk Modeling: AI, Geospatial Intelligence, and Deep Learning

Modern flood modeling has evolved beyond deterministic, physics-based hydraulic simulations toward a fusion of data-driven, probabilistic, and hybrid approaches. Traditional models such as HEC-RAS, GSSHA, and LISFLOOD remain essential for riverine and stormwater modeling, but they are increasingly complemented—and in some applications, outperformed—by artificial intelligence and machine learning (ML) models that ingest vast amounts of structured and unstructured data.

Machine learning techniques, particularly deep learning approaches like convolutional neural networks (CNNs), recurrent neural networks (RNNs), and ensemble models, are proving particularly adept at handling large-scale geospatial datasets with complex, nonlinear interactions. These models can be trained using satellite imagery, sensor outputs, digital elevation models, historical flood extents, and meteorological inputs to produce rapid, high-resolution flood predictions. Compared to traditional models, they are less sensitive to missing data, can learn from past events, and adapt quickly to new observations.

A key advantage of these models is their ability to address common issues in flood modeling such as spatial autocorrelation, data imbalance, and model uncertainty (Koldasbayeva et al., 2023). For example, decision tree ensembles can be used to downscale precipitation forecasts, while deep CNNs can map inundation from satellite-derived flood extents even when the terrain or land cover varies significantly. Bayesian networks and probabilistic graphical models offer further tools to quantify the uncertainty of flood predictions and simulate cascading impacts across infrastructure networks.

Real-time integration is a central strength of AI-based modeling frameworks. As flood sensor networks and remote sensing platforms generate continuous data streams, machine learning models can update their forecasts with minimal delay, improving both short-term warning accuracy and long-term risk assessments. This enables the development of dynamic flood early warning systems (FEWS) that evolve in real time based on the behavior of incoming weather systems and observed water levels.

The insurance and reinsurance industries have become early adopters of these capabilities. Using geospatial artificial intelligence (GeoAI), insurers are integrating structured flood data, remote sensing imagery, climate variables, and social vulnerability indices into portfolio-scale risk engines. These engines continuously recalculate exposure metrics across millions of policies, enabling insurers to assess both near-term threats and climate-adjusted risk profiles (Whitehair, 2024). This dynamic capability supports risk-based pricing, post-event claims triage, and regulatory compliance with solvency standards under climate stress scenarios.

Flood modeling powered by AI is also transforming urban planning and resilience

efforts. Municipalities can use predictive analytics to evaluate different infrastructure investment strategies under future flood scenarios, while water utilities can pre-position maintenance teams based on forecasted pipe inundation or pump station failures. Cloud-based modeling environments—often integrated into digital twin platforms—allow for collaborative scenario testing among engineers, planners, and emergency managers.

Despite its promise, AI-based flood modeling is not without challenges. Data availability, model explainability, and the risk of algorithmic bias remain critical concerns. Ensuring transparency, reproducibility, and stakeholder trust in AI-driven decision support tools will require the adoption of open-source frameworks, standardized validation benchmarks, and continuous community engagement.

Nonetheless, the rapid maturation of AI and GeoAI tools, particularly when combined with traditional hydrologic models and domain expertise, is ushering in a new era of intelligent, adaptive, and anticipatory flood risk management.

In the study on strengthening community resilience through enhanced flood analytics, AIR Worldwide explored how machine-readable data pipelines and cloud-based platforms could support data fusion across agencies and vendors. The *Enhancing Flood Analytics Study* emphasized the role of automated intelligence and remote sensor integration in streamlining risk assessments and supporting near real-time model updates. The report detailed a prototype analytics platform that ingested data from sensors, satellite images, and structure inventories to provide continuous exposure updates. Using AI-enabled event detection, the system could automatically flag buildings likely to be inundated and estimate damage distributions within minutes of flood onset (AIR Worldwide, 2019b).

Another key finding was the potential for this approach to improve post-disaster damage verification, reducing the lag between event and payout in flood insurance or federal assistance contexts. Automated exposure mapping and model-based loss estimates helped validate claims in real time, especially when field verification was constrained by access or safety concerns. These capabilities are helping flood analysts reduce modeling latency, improve event detection, and better communicate exposure across stakeholders.

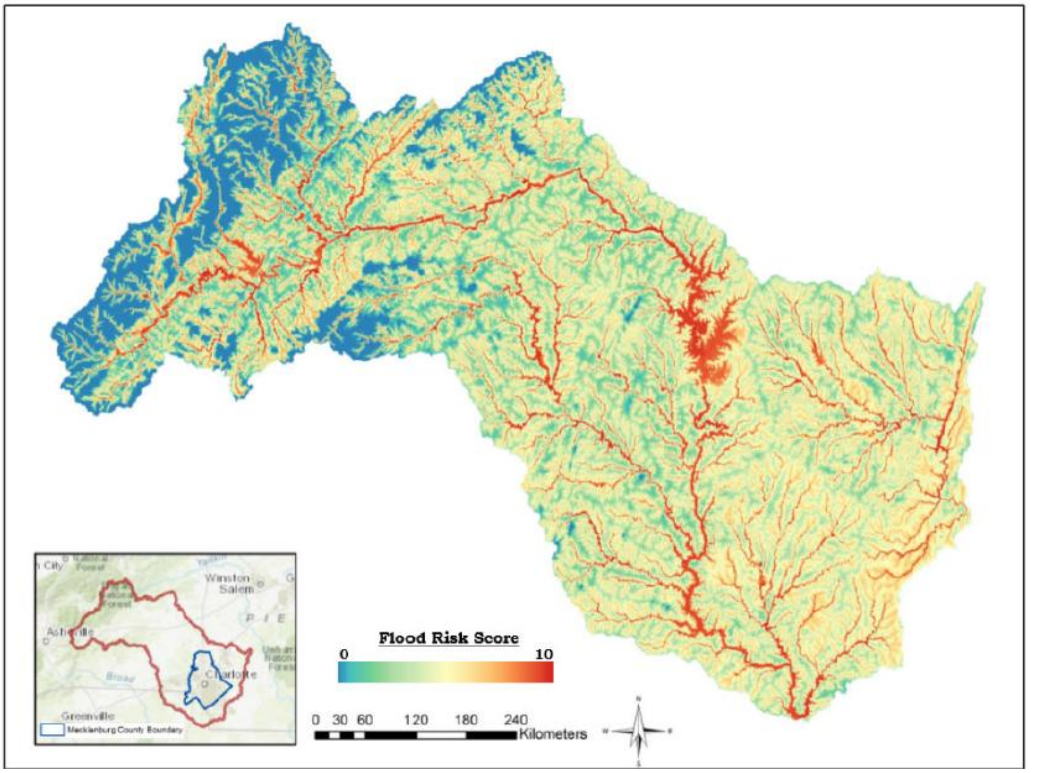


Fig. B: *Flood Risk using Automated data pipelines and exposure mapping*

Flood risk score on a 1 to 10 scale at high spatial resolution of 10m grids for Mecklenburg County and its contributing watershed.

6. Emerging Technologies: Digital Twins, Augmented Reality, and Decision Support

Digital twin technologies create real-time, virtual representations of physical environments, enabling decision-makers to simulate, visualize, and manage flood risk with unprecedented fidelity. These digital replicas are dynamically linked to live data feeds, including IoT flood sensors, satellite imagery, hydrologic models, and weather forecasts, providing an integrated and continuously updating situational picture. By mirroring real-world systems—such as drainage networks, transportation infrastructure, and building footprints—digital twins empower emergency managers, urban planners, and engineers to test scenarios, monitor changing conditions, and optimize response strategies.

In flood-prone cities, digital twins are increasingly used to model the impact of heavy rainfall or river overflow events in real time. For example, when combined with predictive hydrodynamic models and real-time stream gauges, a digital twin can simulate the spread of floodwaters across a city block-by-block, helping to forecast

which intersections will flood first or which critical facilities are likely to be cut off. These insights support timely evacuation planning, emergency vehicle routing, and shelter placement.

Artificial intelligence embedded within digital twins can further enhance their utility by analyzing historical and real-time data to predict asset vulnerabilities, recommend adaptive measures, and even automate warning alerts. Algorithms trained on historical flood damage records can simulate potential loss scenarios and prioritize mitigation investments accordingly. Traffic optimization tools within digital twins can suggest alternate evacuation routes based on projected road inundation.

Augmented reality (AR) expands the accessibility and impact of flood data by making it immersive and intuitive. Using mobile apps or headsets, residents, planners, and public officials can visualize flood risks overlaid on their physical surroundings. For example, homeowners can see projected flood depths within their property boundaries during a 100-year or 500-year flood event, increasing risk awareness and prompting protective actions. Municipal workshops have begun using AR to engage the public in participatory planning, allowing communities to "walk through" future flood scenarios and explore mitigation options collaboratively.

These emerging technologies are also transforming training and preparedness. First responders can use virtual reality (VR) or AR simulations to practice flood response scenarios in lifelike environments. Public works departments can explore system vulnerabilities in a 3D digital replica of their infrastructure network. Local governments can conduct virtual tabletop exercises where agencies coordinate responses within a shared, data-driven environment that reflects real-world complexities.

When integrated with geospatial platforms like ArcGIS, digital twins and AR interfaces become part of a broader decision support ecosystem. This ecosystem allows data from disparate sources—ranging from building inventories and pipe networks to rainfall forecasts and social vulnerability indices—to be fused into a single operational dashboard. Such platforms support risk communication, real-time monitoring, and post-disaster impact assessment.

The long-term potential of these tools lies in their scalability and adaptability. As climate hazards evolve and urban systems grow more complex, digital twins can evolve with them—incorporating new sensors, hazard models, and user inputs. Their modularity makes them well-suited for integration into smart city infrastructure and resilience planning efforts, particularly when paired with funding from federal programs like the BRIC initiative or the Community Development Block Grant–Disaster Recovery (CDBG-DR).

As climate volatility increases, digital twins, AR, and integrated decision support systems will be indispensable for proactive mitigation and adaptive recovery. These technologies bridge the gap between data and action, offering communities the tools to not only see their risks—but to manage them in real time, with foresight and flexibility.

As noted in the *Enhancing Flood Analytics Study*, digital twins are also being piloted in

the context of operational floodplain management, with early success in applications for local hazard planning and stormwater infrastructure monitoring. One demonstration project highlighted in the study involved overlaying real-time water levels and rainfall rates on a digital representation of Baton Rouge's drainage network. The system visualized impending overflows and issued alerts to city staff in advance of structural flooding. This integration of forecast modeling, IoT data, and digital representation created a powerful feedback loop between risk awareness and operational decision-making (AIR Worldwide, 2019b).

The report also emphasized that digital twins support cross-agency collaboration by providing a shared visual and data-rich environment for planning. Planners, utilities, and emergency managers could collaboratively assess vulnerabilities, simulate mitigation measures, and coordinate public communications using the same dynamic system. These features extend the value of digital twins beyond modeling—into governance and crisis coordination.

7. Conclusion: Toward a More Intelligent Flood Resilience System

Provisioning better data for flood risk management is no longer a technical luxury—it is a foundational requirement for resilience. From the sensor on a rural stream gauge to the satellite 500 miles above Earth, modern technologies are producing a deluge of valuable data. Yet the true value lies in integration: bringing together sensor feeds, structured building inventories, AI-powered models, and immersive tools into coherent, accessible systems.

The next phase of flood resilience will hinge on continued investment in open data standards, cross-sector partnerships, and intelligent infrastructure. It will also require addressing equity gaps, ensuring that all communities, regardless of size or wealth, have access to the data and tools they need to prepare for and withstand flood disasters. The challenge is immense—but so is the opportunity to build a smarter, safer, and more resilient future.

The DHS S&T-funded *Comparative Flood Hazard Estimates Study* and *Enhancing Flood Analytics Study* stand out as landmark efforts in interagency innovation. By evaluating the limitations of existing mapping systems and piloting forward-looking analytics tools, these studies demonstrate how coordinated federal investments can accelerate both technical advancement and operational preparedness. Their integration of high-resolution sensing, machine learning, and digital modeling provides a blueprint for collaborative, cross-sector progress in managing flood risk at scale.

8. Key Themes, Questions, and Additional Readings

8.1 Key Themes

1. Real-Time Sensing: IoT flood sensors and satellite platforms offer timely, ground-to-orbit visibility into changing flood conditions.
2. Structured Data: National building inventories and LIDAR elevation data enable precise exposure modeling at the parcel level.

3. Modeling Innovations: AI and machine learning enhance flood prediction, risk mapping, and decision support with adaptive capabilities.
4. Immersive Technology: Digital twins and AR transform risk communication, simulation, and public engagement for climate resilience.
5. Equity and Access: Better data must be paired with equitable tools and policies to serve underserved and flood-prone communities.
6. Interagency Innovation: Federally supported analytic studies like those from DHS S&T highlight how partnerships across science, policy, and emergency management can drive innovation.

8.2 Discussion Questions

1. How do IoT flood sensors enhance local response capabilities compared to traditional gauge systems?
2. In what ways do structured building datasets improve the accuracy and equity of flood risk modeling?
3. What are the trade-offs between physics-based and AI-based flood models? How might they be combined?
4. How can emerging tools like AR and digital twins support both emergency response and long-term resilience planning?
5. What challenges remain in ensuring that advanced data tools are accessible to smaller or under-resourced jurisdictions?

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Flood Proofing Standards and Technology Innovation in Lowering Flood Risks and Damages

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Abstract

Floodproofing technologies—paired with rigorous standards, testing, and certification—are reshaping disaster resilience. Focusing on the ANSI/FM 2510 standard and the National Flood Barrier Testing and Certification Program (NFBTCP), the chapter illustrates how verified flood mitigation products can enhance building protection, streamline public procurement, and deliver high returns on investment. Through domestic and international case studies, including examples from Alton, Illinois and the Netherlands, the chapter highlights the role of innovation, public-private partnerships, and policy integration in scaling adoption. By advancing national and global floodproofing standards, communities can reduce risk, ensure code compliance, and build toward a more resilient future.

Keywords

Flood proofing, flood barriers, standards, ANSI

1. Introduction

Flooding remains the most frequent and damaging natural disaster in the United States, responsible for the greatest loss of life and the highest economic damages among all natural hazards. From urban flash floods to coastal storm surges, flood risk is intensifying across regions due to climate change, sea level rise, and the expansion of built environments into flood-prone areas. According to the Association of State Floodplain Managers (ASFPM), annual flood damages have grown from an average of $5.6 billion in the 1990s to an estimated $17 billion per year in the past decade (ASFPM, 2020).

Flooding can result in widespread destruction throughout a community—disrupting lives, damaging property, and destabilizing local economies. Increasing flood resilience requires a range of mitigation actions, and among the most promising strategies is the development and expansion of national and international

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floodproofing standards. Innovation in product design—ranging from barrier systems and valves to coatings and pumps—has accelerated in recent years, offering practical, scalable, and often cost-effective tools for adaptation.

Central to the successful deployment of these technologies is a rigorous framework of standards, testing, and certification. Programs such as ANSI/FM 2510 and the National Flood Barrier Testing and Certification Program (NFBTCP) have created essential benchmarks for safety, durability, and performance. Coupling these standards with third-party testing offers multiple benefits for manufacturers, consumers, emergency managers, and code enforcement officials alike. As ASFPM (2020) emphasized, national flood resilience standards and testing "give property owners and municipalities the peace of mind that comes from knowing the flood-fighting products they're using to protect their facilities meet the most rigorous standards in terms of quality and performance."

Floodproofing interventions are particularly valuable because they can be customized to individual properties, installed quickly, and used in areas where traditional structural interventions such as levees or diversion channels may be impractical or prohibitively expensive. From hospitals and transit hubs to small businesses and historic buildings, floodproofing solutions can reduce both structural damages and business interruption costs. In this context, floodproofing is not merely a retrofit strategy but is becoming central to climate adaptation and community resilience.

Nationally recognized standards, coupled with technological innovation, represent the frontier of modern flood mitigation—one grounded in science, supported by policy, and increasingly demanded by communities confronting intensifying risk.

2. Floodproofing and Barrier Protection Standards



Fig 1: *Flood Proofing Technology Examples: Photos Courtesy of ASFPM (2019).*

Floodproofing measures are designed to reduce the impact of floodwaters on buildings and infrastructure by resisting, repelling, or redirecting water. These interventions serve as both primary and supplemental defenses, and they are particularly useful in urban, coastal, and retrofit scenarios where traditional infrastructure may be impractical or insufficient. These measures include both temporary and permanent systems, each designed to serve a distinct protective function:

- Perimeter barriers (e.g., stackable flood walls, inflatable dams): These systems are deployed around a structure or property to form a protective ring or wall that blocks incoming floodwaters. Stackable flood walls consist of modular panels that can be quickly assembled in advance of a flood event, while inflatable dams use water or air pressure to create a temporary flood shield. They are particularly useful for commercial properties or critical infrastructure.
- Closure devices (e.g., flood doors, panel systems): Closure devices are installed at building entry points such as doors, windows, and garage bays. They are designed to seal off these vulnerable openings and can be either permanently installed or manually deployed. Some systems include compression seals and locking mechanisms to ensure water-tightness under pressure.
- Penetration sealing devices: These systems protect against water intrusion at pipe penetrations, conduit entries, and other wall or floor penetrations. They often use elastomeric or mechanical seals that expand in the presence of water to form tight closures, helping to protect utility and mechanical systems.
- Flood mitigation valves and pumps: Backflow prevention valves and sump pumps are critical to managing internal water pressure and preventing sewer and storm drain backup during flooding. These systems often activate automatically and are designed to keep basements and lower levels from inundation.
- Flood glazing and coatings: Specially treated window systems and exterior coatings provide an additional layer of protection against both hydrostatic pressure and debris impact. Flood glazing can resist water penetration and breakage, while hydrophobic coatings on walls can minimize water absorption and facilitate faster post-flood clean-up.

Until recently, the performance of these products was largely unregulated, and many systems failed under real-world conditions due to insufficient testing. A patchwork of manufacturer claims and inconsistent laboratory methods left emergency managers and local officials with limited confidence in available solutions. To address this, FM

Approvals developed ANSI/FM 2510-2020, a national standard that outlines a rigorous set of testing and performance requirements for flood mitigation products.

The standard evaluates performance across multiple dimensions, including:

- Hydrostatic strength and leakage: Measures a product's ability to withstand prolonged water pressure without structural failure or seepage.
- Impact, vibration, and abrasion resistance: Ensures products can endure contact with floodborne debris and mechanical stress without compromising integrity.
- Corrosion and UV degradation: Tests materials for resilience under prolonged exposure to water, sunlight, and environmental contaminants.
- Extreme temperature operation and environmental aging: Evaluates functionality in freezing or high-heat conditions, and under prolonged storage or seasonal exposure.
- Tear, puncture, and tensile performance: Assesses durability against punctures and stresses, particularly for flexible barriers and membranes.
- Biological and environmental durability: Examines susceptibility to mold, mildew, rot, and chemical exposure, which can degrade long-term performance (FM Approvals, 2020).

In doing so, ANSI/FM 2510 allows for a common baseline by which engineers, building owners, local governments, and insurers can assess flood protection systems with confidence. Certification levels under the standard range from silver to platinum, though most manufacturers opt for the platinum level—indicating their product can withstand hydrostatic water levels up to four feet. This certification is critical not only for quality assurance, but for regulatory compliance and eligibility under federal mitigation programs. Third, the presence of certification reduces uncertainty, enabling jurisdictions to incorporate floodproofing into local hazard mitigation plans and resilience investments.

The analysis also highlighted the program's sensitivity to adoption rates. Monte Carlo simulations showed that even under conservative assumptions, the net benefits remained robust, ranging from $154 million to $861 million across different scenarios. Adoption by public sector facilities—such as water treatment plants, fire stations, and schools—was found to be especially impactful given the societal value of keeping those services operational during flood events.

3. National Flood Barrier Product Testing and Certification

The National Flood Barrier Testing and Certification Program (NFBTCP) was launched in 2012 through a collaboration between DHS Science and Technology Directorate (S&T), ASFPM, the U.S. Army Corps of Engineers (USACE), and FM Approvals. The program seeks to bridge the gap between engineering innovation and market reliability by establishing an independent, third-party system to test and certify the performance of floodproofing technologies.

Testing is conducted at the USACE's Engineering Research and Development Center (ERDC) in Vicksburg, Mississippi, where a variety of hydraulic conditions can be simulated to test structural durability, seepage, and overtopping. Simultaneously, FM Approvals performs material testing and audits manufacturer quality systems to ensure that products not only pass a single test, but can be reliably manufactured over time. Products that pass the testing regimen receive the FM Diamond, a globally recognized certification mark akin to Underwriters Laboratories (UL) certification for fire protection equipment.

To date, thirteen products have been certified under this program, spanning a range of applications from residential flood panels to industrial barriers. These include modular wall systems, aluminum flood doors, inflatable perimeter dams, and pedestrian flood gates. Companies such as Tiger Dam, AquaFence, Presray, and PS Flood Barriers represent a growing segment of the market that recognizes certification as a value-add for customers and a path to international competitiveness.

4. Advancing Flood Mitigation through Flood-Resistant Design Standards

While product certification is essential, its true value is realized when integrated into broader flood-resistant design strategies and building code frameworks. FEMA's forthcoming update to Technical Bulletin 3 (TB-3), which governs dry floodproofing for non-residential structures, is expected to directly incorporate ANSI/FM 2510 references. This update will clarify acceptable methods for installation, maintenance, and compliance—removing ambiguity and strengthening building officials' confidence in product-based floodproofing systems (FEMA, 2020).

Complementing these standards are advances in urban flood resilience technologies. Smart flood sensors, powered by low-energy IoT networks, are now capable of providing real-time warnings at street level. Companies like LiXiA have piloted systems that integrate low-cost solar sensors with municipal alert platforms, enabling communities to dynamically assess conditions during storm events (The Courier-Mail, 2024). These sensors are particularly useful in cities with combined sewer overflows or flash flood vulnerabilities.

Self-closing flood barriers (SCFBs) represent another breakthrough. Using the buoyant force of incoming water, these barriers deploy autonomously without human intervention. Found in locations such as subway entrances, hospital loading docks, and fire stations, SCFBs ensure continuity of operations for critical facilities even during rapid-onset flood events (Wikipedia, 2024).

Additionally, green infrastructure solutions like permeable paving and bioswales are increasingly incorporated into flood mitigation design. While not replacements for certified structural systems, these nature-based interventions can dramatically reduce stormwater volumes and improve infiltration, especially in urban redevelopment zones (EPA, 2024).

5. Economic Benefits of Floodproofing Standards

Floodproofing standards and certification deliver not just technical benefits, but strong economic returns. As communities face growing pressure to modernize infrastructure and mitigate risk under constrained budgets, the value proposition of pre-disaster investment becomes increasingly compelling. A DHS-sponsored benefit-cost analysis of the National Flood Barrier Testing and Certification Program (NFBTCP), conducted by the CREATE research team at the University of Southern California, found that the program generated $272.48 million in net benefits over a 10-year period—with a benefit-cost ratio of 12.9 and a return on investment exceeding 1,100% (Wei, Rose, & Machado, 2019).

These benefits accrue across multiple dimensions. First, certified products significantly reduce the likelihood and severity of structural failure, leading to reduced property losses, lower insurance payouts, and faster recovery times. Structures protected by certified floodproofing systems are more likely to remain operational during and after flood events, which is crucial for critical facilities such as hospitals, emergency services, utilities, and transportation hubs.

Second, the presence of standardized certification facilitates clearer and more efficient decision-making among stakeholders. Building owners, contractors, insurers, and public agencies can make informed comparisons between products, knowing they meet tested and uniform benchmarks. This market clarity drives competition, rewards innovation, and supports the creation of high-quality products with known performance characteristics.

Third, the certification framework helps jurisdictions incorporate product-based flood mitigation into local hazard mitigation plans and resilience strategies. Because certified products are recognized under FEMA guidelines and increasingly referenced in model codes, communities can streamline their regulatory processes and unlock access to federal funding opportunities.

Importantly, the benefit-cost analysis highlighted the program's sensitivity to adoption rates. A Monte Carlo simulation showed that even under conservative assumptions—such as low product uptake or minimal avoided losses—the net benefits remained robust, ranging from $154 million to $861 million across different scenarios. Public sector adoption had especially high returns, given the social and economic consequences of service disruptions at facilities like water treatment plants, emergency response stations, and public schools. Investing in floodproofing for these buildings preserves functionality and reduces long-term disaster recovery costs.

Additionally, there are intangible benefits not easily captured by financial modeling. These include enhanced public confidence, lower risk perception among businesses and residents, and the reputational advantages for jurisdictions that proactively adopt visible, certified flood defenses. In a competitive funding and insurance environment, demonstrating resilience through certified infrastructure can also lead to reduced premiums, higher bond ratings, and eligibility for resilience-based grants and investment programs.

Altogether, floodproofing standards support a virtuous cycle of risk reduction, market innovation, and financial efficiency—one that positions communities not only to survive future flood events, but to thrive despite them.

6. Case Studies

Alton, Illinois: Adaptive Downtown Flood Wall

In Alton, Illinois, a riverside community along the Mississippi, planners faced considerable public resistance to an initial proposal for a large floodwall intended to protect downtown from periodic river flooding. Residents and business owners expressed concern that the structure would obstruct scenic river views, interfere with the walkability and character of the historic downtown area, and potentially reduce tourism and commercial vitality. In response, city officials embarked on an inclusive community engagement process involving public forums, stakeholder charrettes, and technical consultations.

The final design emerged as a hybrid solution—featuring a 3-foot permanent concrete wall that blends with the streetscape, paired with stackable, deployable barrier panels that can be installed quickly when a flood threat emerges. The revised plan also includes shutoff valves at stormwater outlets and a new pumping station to manage backflow during high-water events. This layered approach balances protection with aesthetics, functionality with flexibility. The Alton project is notable not only for its engineering innovations but also for its use of emerging ANSI/FM 2510-compliant technologies and its emphasis on public transparency. It serves as a model of how adaptive infrastructure can align with both national standards and community values (The Telegraph, 2025).

The Netherlands: A Global Benchmark for Integrated Flood Management

The Netherlands has long led the world in flood control and water management, a necessity given that more than a quarter of the country lies below sea level. While the Dutch historically relied on an extensive system of dikes, dams, and pumps, in recent decades their strategy has evolved to embrace nature-based solutions and multifunctional infrastructure through the "Room for the River" initiative.

This nationally coordinated program integrates spatial planning, engineering, and ecological restoration to reduce flood risk while enhancing environmental and social outcomes. Examples include widening river channels, lowering floodplains, creating secondary watercourses, and constructing underground parking garages that double as emergency stormwater storage during high water events. Cities like Rotterdam and Nijmegen have redesigned waterfront districts with elevated structures, deployable barriers, and recreational spaces that transform into retention zones during floods.

Dutch engineering firms have also led the charge in developing advanced floodproofing technologies—such as automatic closing floodgates and water-resistant materials—that align with global standards, including ANSI/FM 2510. These products are increasingly being exported to the U.S. market, demonstrating a convergence of international best practices. The Dutch model exemplifies how flood resilience can be

embedded into the fabric of urban development and how global knowledge-sharing strengthens national adaptation strategies.

Table 1: Selected Certified Floodproofing Products

Product Name	Manufacturer	Type	Certification
Tiger Dam Perimeter Barrier	US Flood Control	Temporary Barrier	ANSI/FM 2510 – Platinum
AquaFence V1200	AquaFence	Modular Wall Panel	ANSI/FM 2510 – Platinum
Presray FB33	Presray	Adjustable Door Barrier	ANSI/FM 2510 – Platinum
PS Doors FP-530FM	PS Flood Barriers	Flood Plank	ANSI/FM 2510 – Platinum

7. Conclusion

Floodproofing standards and certification programs have become essential tools in the national effort to reduce disaster losses. The development of ANSI/FM 2510 and the implementation of the NFBTCP have created a performance-based foundation for innovation, trust, and broader adoption of mitigation technologies. These frameworks empower communities, manufacturers, and emergency managers to make informed decisions in selecting and deploying flood protection systems.

But more work remains. The scaling of floodproofing technologies will depend on removing financial and regulatory barriers to adoption, especially in vulnerable communities. Increased integration with HUD resilience funding, FEMA mitigation grants, and state-level incentive programs could accelerate uptake. Education and outreach, especially among code officials, insurers, and the construction industry, will be critical.

Looking forward, the continued success of this approach will depend on widespread integration into building codes, proactive public-private partnerships, and sustained investment in emerging technologies. As the impacts of flooding intensify across the nation, resilient, standardized, and innovative floodproofing will be key to reducing risk—and rebuilding smarter.

8. Key Themes, Questions, and Additional Readings

8.1 Key Themes:

- The growing role of floodproofing in national resilience strategies.
- The importance of ANSI/FM 2510 in creating a standard of quality and safety for flood mitigation products.
- Integration of certified technologies into building codes, hazard mitigation planning, and public procurement.
- The economic value and return on investment from certified flood protection systems.
- The convergence of infrastructure innovation, public engagement, and global collaboration.

8.2 Discussion Questions:

1. How do floodproofing standards like ANSI/FM 2510 help ensure product performance in real-world flood conditions?
2. In what ways can certification programs like NFBTCP influence public and private sector investment decisions?
3. What are the limitations of relying solely on structural floodproofing measures, and how can they be addressed?
4. How might international models, such as the Netherlands' "Room for the River," inform U.S. flood resilience strategies?
5. What policy levers could help scale the adoption of floodproofing technologies in low-resource or high-risk communities?

8.3 Additional Readings:

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Social Equity Data needs and access for disaster resilience

Cassandra Davis, Phil Berke, and Miyuki Hino[107]

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Abstract

There is growing evidence that socially marginalized populations and communities are disproportionately affected by emergencies and thus more susceptible to disasters. There is still little consensus on definitions, the indicators, or indices to use, and the approach to measure social (in)equity. This project employed a conceptual framework for embedding equity in disaster risk management, including distinguishing between equality and equity. The framework was applied to four North Carolina communities, examining each component: historical context, plan-based indicators, social vulnerability indicators, and community voice. Preliminary results point to inconsistencies and gaps within these components suggesting the need for a more inclusive, comprehensive planning approach to better serve socially marginalized interests. However, additional research is needed to address key questions on the role of community planning in disaster resilience and hazard mitigation.

Keywords:

Social equity, equality, vulnerability

1. Introduction

"Fairness does not mean everyone gets the same. Fairness means everyone gets what they need." (Riordan 2010)[108]

Federal agencies have recognized the threats of climate change as it magnifies the risks from hurricanes, flooding, and wildfires (DHS, 2012; FEMA, 2021; NOAA, 2021; NASA, 2021; EPA, 2021). One of the most consistent findings in climate change and disaster research is that socially marginalized populations are disproportionately more susceptible to hazards and are less likely to recover completely and quickly (Davis et al., 2021; Rodriguez-Díaz & Lewellen-Williams, 2020; Flanagan, B., 2011; Castle &

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[108] Rick Riordan (2010) The Red Pyramid. Disney Hyperion Books. New York, New York. April 28, 2010.

Engberg, 2011; Fothergill & Peek, 2015; Tierney, 2019). One approach to supporting socially marginalized populations is accurately assessing and addressing vulnerability using indices (Flanagan et al., 2011). Through this process, Flanagan and colleagues (2011) argued that one could effectively decrease financial loss and human suffering.

Until recently, scholars have noted inconsistencies amongst existing indices that are used to identify marginalized groups, aid disaster recovery planning, and support local and national policy decisions (Rufat et al., 2019; Goodman et al., 2021). As hazardous events increase with intensity and frequency (EPA, 2021), we need a better way to improve the measurement of outcomes for marginalized groups to guide resiliency and disaster recovery planning. More accurate measures could allow state and federal agencies to pro-actively provide support for mitigation and recovery based on community needs. However, improving the precision of indices may not be enough. Instead, we argue the necessity of applying social equity as a framework for improving how vulnerability is measured, tracked, and assessed.

This paper aims to provide preliminary evidence on how local, state, and federal policymakers can effectively develop and implement equitable strategies to support marginalized groups before, during, and after extreme events and help guide resilience planning. To achieve this, we identified four case study sites, reviewed relevant literature, and constructed a conceptual approach tailored to decision-makers dealing with hazard mitigation, disaster recovery, and community adaptation to climate change. Using the conceptual approach as a framework for exploration, we delve into the historical context of case study sites, reviewed their hazard mitigation and comprehensive plans to identify gaps, assessed the efficacy of existing vulnerability metrics within sites, and defined community voice. But before we provide our analysis, we must distinguish between equality and equity in the disaster risk management community.

2. Equality v. Equity

The United Way (2022) defined equality as “the state of being equal, especially in status, rights, and opportunities. Equality means each individual or group of people is given the same resources and opportunities, regardless of their circumstances” (para 2). Where equality can be viewed as a tool to “level the playing field” across groups, it also creates substantial inequalities for marginalized populations.

In Figure 1, we provide an example of how equality can result in advantages for one and disadvantages for another. This figure shows three people experiencing a flood differently. Person A is in a sailboat, Person B is in a rowboat, and Person C is in the water. Using an equality lens would suggest that each person receives the same support to overcome the emergency. In this example, everyone received a life jacket. An equality lens denies the differences in needs based on each person and does not account for external circumstances that better determine needs.

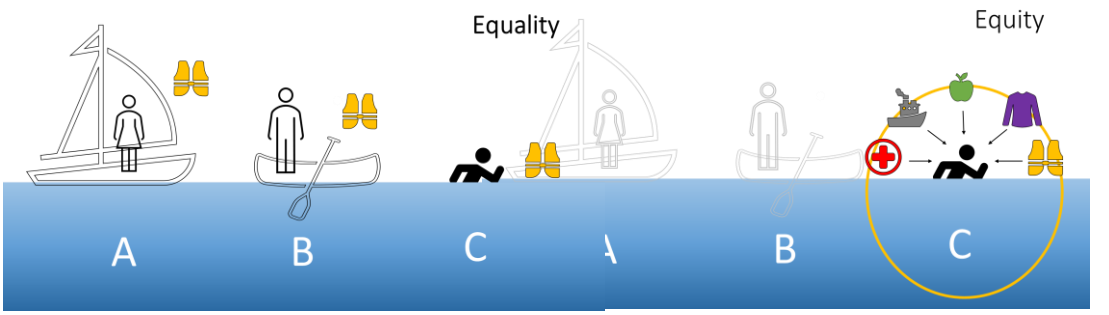


Fig. 1: *Equality vs. Equity*

In contrast, an equitable lens provides a space that acknowledges the imbalances between groups and offers appropriate support based on group needs. The Urban Strategies, Inc. (2021) defined social equity as a tool to "first address the disparities and barriers on individual, systemic, and structural levels, then use this information and data to provide opportunities for success to individuals based on their right of access and specific needs" (para 6). An equitable lens offers a framework to assess the context, history, environment, and other attributes that determine the variation of needs and provide the appropriate support. Using an equitable lens, Person C in the right example, is given various options to assist them during an emergency.

The literature reveals that marginalized populations are more likely to represent Person C – an individual with limited access to support for past, present, and future events. Marginalized populations face disproportionally higher risks from climate hazards (Davis et al., 2021; Rodriguez-Díaz & Lewellen-Williams, 2020; Castle & Engberg, 2011; Fothergill & Peek, 2015; Tierney, 2019). History reveals that this group tends to be people of color (Rodriguez-Díaz & Lewellen-Williams, 2020), people representing low-income households (Tierney, 2014; Baker & Cormier, 2015), women (Enarson, 2012), the elderly (Luft, 2016), children (Peek, 2008; Davis, Cannon & Fuller, 2022), unhoused individuals (Méndez et al., 2020), differently-abled individuals (Stough et al., 2016), immigrants (Nguyen & Salvesen, 2014), and others (Davis et al., 2021).

3. Conceptual Framework

With few examples of equity within the realm of community resilience to disasters, the authors used literature from multiple disciplines such as business, economics, education, philosophy, public health, and urban planning to construct a disaster risk management conceptual approach invested in social justice. Our review of 30 equity frameworks revealed that equity was used as a foundation for establishing systemic change and not as an add-on that supports surface-level modifications. Equity frameworks tended to include a space that reflects the histories of oppression and a space for community input and perspective. The findings also revealed that equity frameworks provided a method to evaluate progress and intentionally identify the marginalized group impacted.

The authors constructed a conceptual framework (Figure 2) for the decision makers that deal with hazard mitigation and community adaptation to climate change. We established the following mission, "to measure, monitor, and determine progress to advance equitable and resilient outcomes for marginalized populations." Our framework contains three stages; (1) Identify inconsistencies, (2) Identify consistencies and build metrics, and (3) Reach an equitable approach. In the first stage, we identify inconsistencies amongst data sources. We then identify consistencies between data sources in the second stage and build reliable metrics. In the last stage, we can assess the most efficient and equitable approach by allowing the data to validate each other. Within each stage, we focus on four critical dimensions - historical content, plan-based indicators, social vulnerability indicators, and community voice. Ultimately, gathering more data from each dimension allows us to see how marginalized groups recover from a hazardous event.

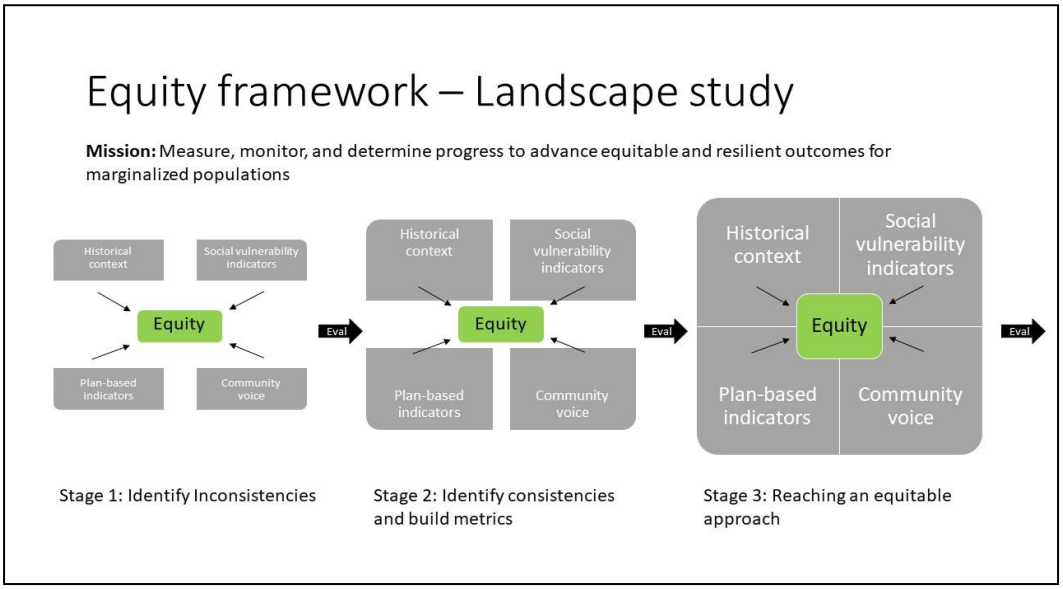


Fig. 2: *Equity framework for the disaster risk management community*

4. Methods

We applied a mixed methods case study design to answer the subsequent overarching research question: How can federal agencies improve the measurement of outcomes for marginalized groups to help guide resilience planning? Case study designs are used when a researcher is interested in exploring a research question through extensive data collection and across multiple sites (Creswell, 2019). The main question prompted the authors to use the equity conceptual framework to guide data collection and analysis in four North Carolina case study sites.

4.1 Research Procedure

First, we identified four North Carolina (NC) case study sites to collect qualitative and quantitative data. Secondly, we reviewed relevant literature on social equity frameworks, social equity in planning, vulnerability metrics, community voice, and resilience procedures for marginalized populations. Our results yielded a review of over 50 articles, government and non-governmental documents, and books related to the topics. The literature review allowed us to construct a conceptual framework for the policymakers and define community engagement through disaster recovery and resiliency. After we reviewed the literature, we reviewed historical archival records to assess oppression and inequalities in the selected NC case study sites.

Next, we reviewed hazard mitigation and comprehensive plans to assess if and how equity indicators were used in local plans. Through this process, we created an evaluation tool to determine the presence of indicators in plans by scoring items based on the degree to which each indicator tracked the effects of planning efforts aimed at meeting the needs of marginalized groups. Indicators that included a community-wide scale received a score of +1, while indicators that differentiated measurements at the sub-community scale received a score of +2. Sub-community scale indicators received a higher score because they helped identify populations in critical geographic areas at greater risk and lacking resources that support equitable outcomes.

For each of the five categories of indicators that we examined (social vulnerability, access to critical services and services, legacies of discrimination, disaster impact and recovery, presence of hazards), we summed the scores for all indicators by type of plan. Higher scores indicate the use of more indicators at the sub-community scale. For instance, suppose four indicators under the 'legacies of discrimination' category were present in a comprehensive plan, and all indicators included scores for different geographic areas (sub-community scale). In this case, the plan received a score of +8. In another example, if three legacy indicators were present in a hazard mitigation plan and two of the three indicators included scores for different areas, then the plan received a score of +5.

In the next strategy, we examined quantitative measures of vulnerability. We cataloged existing databases to develop a broad list of vulnerability indicators, then focused on several of the most commonly used indicators for our subsequent analysis, including the Centers for Disease Control and Prevention – Social Vulnerability Index (CDC – SVI), race, and age. We also evaluated the Climate and Economic Justice Screening Tool (beta version), to support the Biden administration's Justice40 initiative. Finally, we explored the usefulness of post-disaster public assistance records for identifying marginalized populations in our case study communities.

4.2 Sample

The authors reviewed data from 30 counties in North Carolina that represented diversity by region, population, demographics, economic distress, and type of hazard. Based on the culmination of data, we selected four case studies that were illustrative of

the diverse community in NC. Table 1 provides a breakdown of each county selected for the study.

Table 1. Demographics of Sampled Sites

County	Region	Population (k)^	Urban/ Suburban/ Rural*	Non-White Pop~	NC Distress Ranking (2021)+	Median Household Income (2018)+	Type of Hazard(s)[1]
Buncombe	Mountains	269	Suburban	16.1%	67	$53,960	Severe winter storm; Fire; flooding; landslides; mudslides
Burke	Mountains	87	Rural	17.7%	30	$44,946	Severe winter storm; Fire; flooding; landslides; mudslides
Edgecombe	Coastal	48	Rural	63.3%	1	$38,818	Hurricane; flooding
Mecklenburg	Piedmont	1,115	Urban	51.5%	81	$64,509	Flooding

^ https://www.northcarolina-demographics.com/counties_by_population

* https://www.ncruralcenter.org/about-us/

~ https://www.census.gov/quickfacts/NC

+ https://files.nc.gov/nccommerce/documents/Research-Publications/2021-Tiers-memo_asPublished_113020.pdf

1 https://www.fema.gov/disaster/declarations

5. Findings

In the first stage of the conceptual framework, we investigated the inconsistencies across existing data sources used to measure outcomes for marginalized populations. These sources include historical data, planning documents (e.g., hazard mitigation and comprehensive plans), vulnerability metrics, and literature on community voice. This

section summarizes our findings from the first stage for each critical dimension across four NC case study sites.

The first critical dimension to review was the **historical context** of each NC case study site. In this component, we addressed one research question.

1. What are some historical content and unique characteristics of selected NC sites?

In this instance, a review of the historical context shapes past issues of injustices and oppression towards marginalized groups. The archival data revealed conflicting historical narratives between those who were subjugated and the oppressors. Each site (i.e., Buncombe, Burke, Edgecombe, and Mecklenburg Counties) generated great wealth from the exploitation and dependence of free labor from indigenous populations, enslaved and free Blacks to construct roads and railroads (Cutshall, 2021; Worker's Legacy, 2020; Cooper, 2019; Hanchett, 2022). Unfortunately, Black and Brown bodies were not entitled to the wealth produced from their efforts. Burke County had the strongest and longest connection to the manufacturing industry (Worker's Legacy, 2020). Historically, this site was the least racially diverse and permitted children to work in textile mills for extended periods. Today, manufacturing is the largest employer representing about half of the population in the county (Wilki, 2019).

The second critical dimension focused on **planning documents**, specifically the hazard mitigation plans (HMPs) and comprehensive plans (CPs). In this component, we addressed two research questions.

1. To what extent are equity indicators used in different sectors of local planning?
2. How well-coordinated area local agencies share data used for equity indicators?

Findings indicate wide variability in the use of different equity indicators as HMPs and CPs often failed to account for entire categories of equity indicators. First, HMPs in all counties did not include accessibility indicators to essential facilities and services (health care, transit, stormwater drainage) that addressed the root causes of vulnerability of marginalized populations (Figure 3a). However, most CPs (Buncombe, Edgecombe, and Mecklenburg) incorporated accessibility indicators. Second, HMPs in all counties did not include indicators about the legacies of discrimination that reflected racism and segregation practices (e.g., redline maps and exclusionary zoning) (Figure 3b). Two CPs (Ashville in Buncombe County and Charlotte in Mecklenburg County) documented discriminatory practices, while the remaining CPs (Burke and Edgecombe) did not. Third, three of the four CPs did not include equity indicators for tracking disaster losses and recovery rates of households (Figure 3c). Still, HMPs in all counties received higher scores for such indicators. Fourth, there is considerable variability in the use of the fourth indicator - social vulnerability. Both plans in Edgecombe County and Mecklenburg County received equally high scores but plans in Buncombe County and Burke County have considerably lower scores

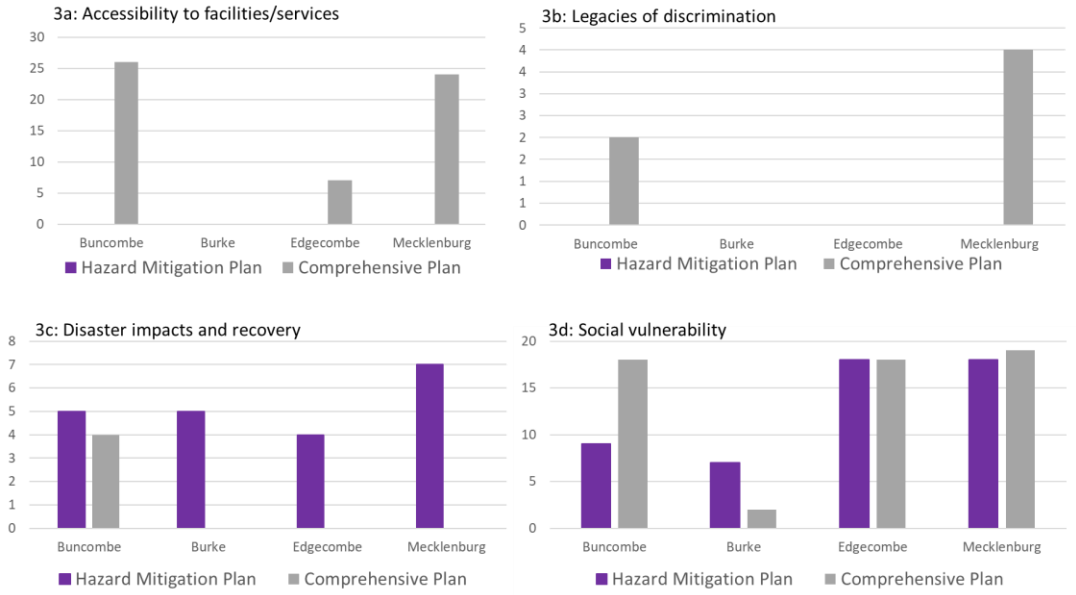


Fig. 3: *Scores for Equity Indicators*

Findings for plans also revealed significant gaps in data sharing needed to create equity indicator metrics to track disparities. First, indicators used in one plan are often not included in the other plan in the same county. For instance, the CP for Charlotte in Mecklenburg County included a wealth of indicators of accessibility to facilities/services and legacies of discriminatory practices. Still, these indicators were absent in the Mecklenburg County HMP (Figures 3a & 3b). Second, all HMPs include maps and data on hazards, but CPs rarely mention or include maps that identify the presence of hazards (Figure 4). Thus, the wealth of equity indicators (i.e., accessibility and legacies of discrimination) are only included in CPs and cannot be used to identify the hazard vulnerability of marginalized populations. Overall, we determined that siloed plans cause missed opportunities to assess inequalities in risks and how disaster events impact marginalized groups.

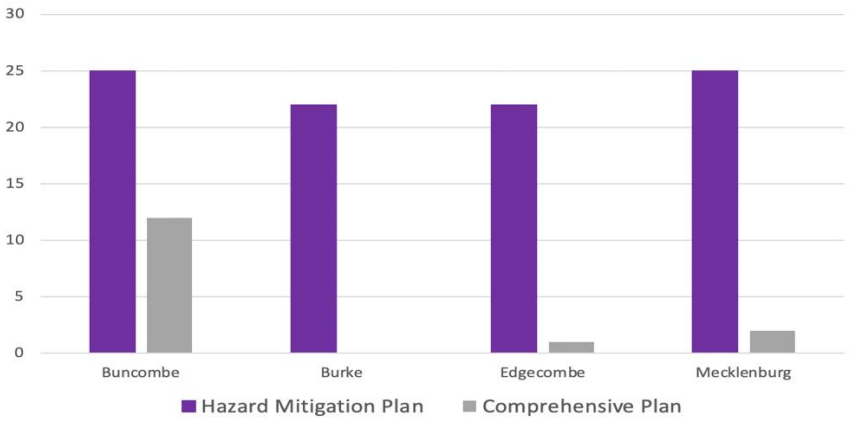


Fig. 4: *Scores for Presence of Different Types Hazards*

The third critical dimension addresses the **social vulnerability indicators**. In this component, we addressed two research questions.

1. What quantitative indicators are currently used to inform equity in resilience plans and investments, and what are the implications of those choices?

2. What indicators of social vulnerability are empirically supported by disaster impact and recovery data?

Our findings revealed that quantitative data from the U.S. Census, CDC's Social Vulnerability Index (CDC SVI), and the Climate and Economic Justice Screening Tool (Justice40 screening tool) yield different results on which communities are more or less vulnerable. For instance, the authors noted disagreement on who is disadvantaged when comparing the CDC SVI to the Justice40 screening tool (Figure 5). The census tracts identified as "disadvantaged" by the Justice40 screening tool are shown in the left-hand panel, and while many of them have high SVI scores, a number also have low SVI scores (below 0.5). Similarly, according to the CDC, several of the "not disadvantaged" census tracts have SVI scores of 0.75 or higher, putting them among the 25% most vulnerable. We find similar differences between other indicators, such as the share of the population in vulnerable age groups, and between these screening tools.

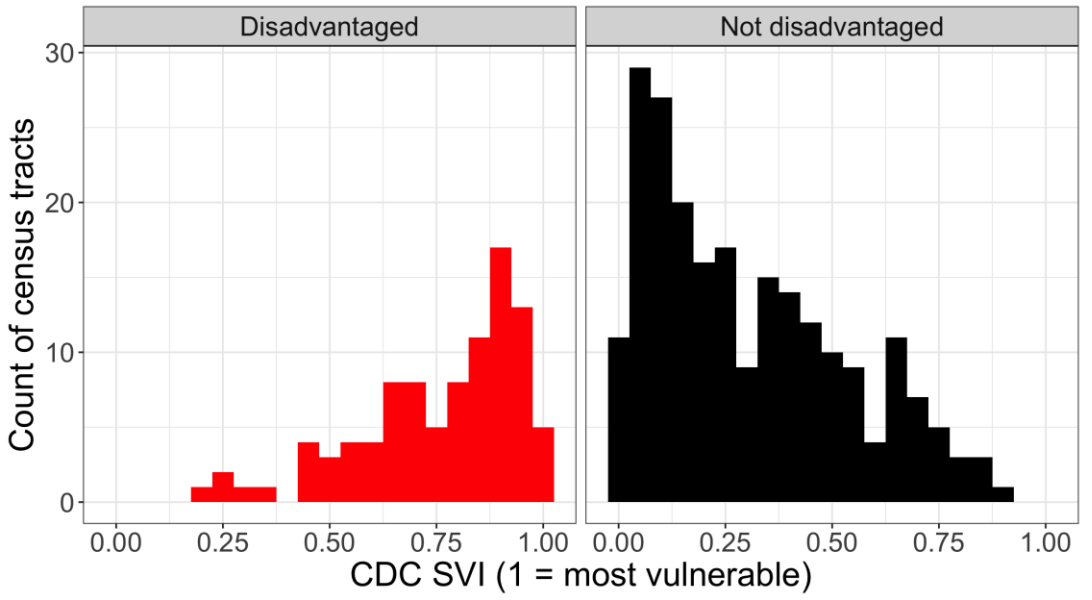


Fig. 5: *Comparing Justice40 disadvantaged and not disadvantaged census tracts as a function of the CDC SVI*

While concerns about the validity of social vulnerability metrics have been expressed widely (Rufat et al., 2019; Goodman et al., 2021), there is scarce empirical evidence to support the selection of indicators for different contexts. We explored the feasibility of using disaster recovery data to assess the validity of potential social vulnerability indicators. Specifically, we reviewed FEMA Individual Assistance data from Edgecombe County to determine who sought government assistance post-disaster and who received it. Examining the income distribution of Edgecombe County overall compared to the income distribution of applicants, we found that applicants for FEMA assistance are disproportionately lower income than the county overall. In addition, our findings showed that a large proportion of ineligible applicants reported a household income of less than $15,000 (Figure 6).

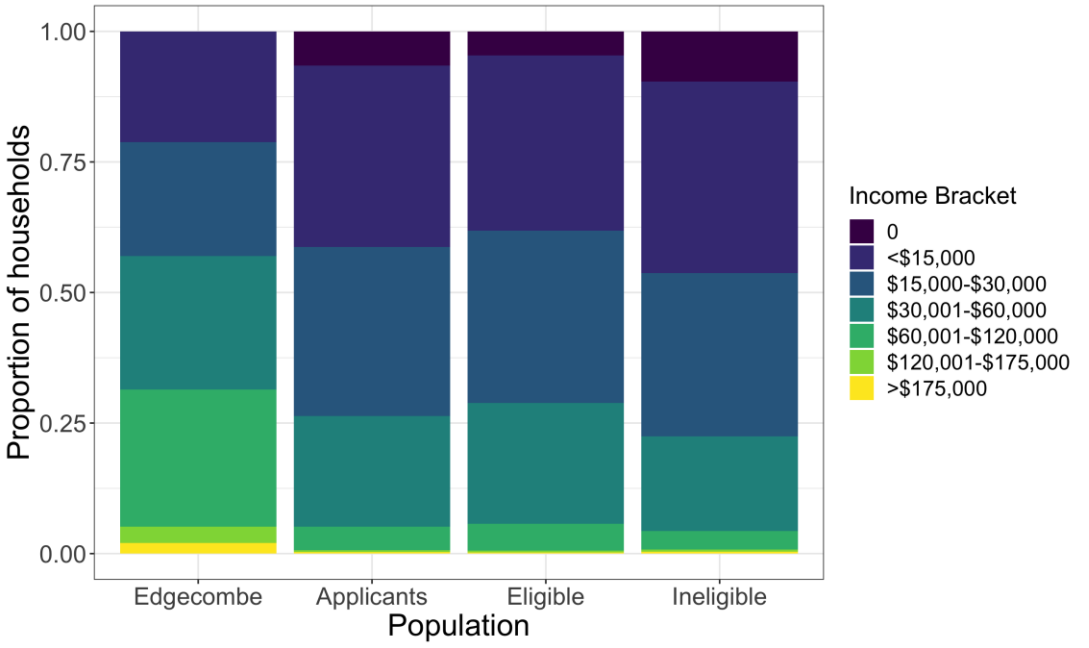


Fig. 6: *Income distribution of: Edgecombe County population, applicants to IHP, eligible applicants to IHP, and ineligible applicants to IHP*

The fourth critical dimension points to identifying and uplifting the community voice of people who are typically underrepresented and excluded from the conversation on planning and disaster risk management. In this component, we address one research question.

1. Whose voice is relevant within the disaster risk management context?

Earlier work suggests that disaster risk management spaces lack representation from ethnic and social groups who are directly impacted by events (Gartrell et al., 2020). Collecting divergent community voices strengthens the disaster planning process and inhibits a monolithic voice from speaking for all. Regardless of intentionality, the process of excluding voices perpetuates oppressive and racist practices that prohibit communal recovery and growth.

Identifying the voices that are present and missing through an equity perspective is vital. Previous literature suggests that the *counter-narratives* – that is, the views of those who are historically left out – are intentionally included as necessary elements of the whole story (Delgado, 1995; Ladson-Billings & Tate, 1995). These individuals tend not to be in power but whose voice is instrumental in challenging the narrative (Dixson & Rousseau, 2005). We suggest that it is still important to continue collecting information from government officials such as firefighters, municipality officials,

planners, and the police. However, it is equally crucial to include community voices such as children, differently-abled persons, local business owners and their staff, migrant population, non-profit organizations (e.g., non-profits and faith-based organizations), school and school district personnel, and unhoused persons. This list is not complete but should help provide directionality in identifying the community voice.

5.1 Policy recommendations

The social equity framework offers a general heuristic for helping identify gaps and ask questions about what type of information is included and left out. We included potential questions at the end of the article for disaster risk management personnel and policymakers to review as they assess social equity in an evolving disaster resilient context. However, we are cautious in providing recommendations as our research is still in the beginning stages of data collection and analysis. From our preliminary assessment, we provide initial recommendations used to guide future work that tackles social equity and disaster risk management.

- **Investigate the history of a community through an equity lens.** The literature on social equity frameworks strongly supports the inclusion of history around oppression. Before entering a community, one must explore how community members helped and harmed each other. An explanation of these different forms of injustice could help explain why one group is less trusting of the other or why one group has been occupying a hazardous space for generations. Understanding the past will allow the disaster risk management community to have a clearer understanding of the equity needs of the community.
- **Support more integration between HMPs and CPs by the community.** Analyzing the HMPs and CPs showed that both plans were likely constructed in silos. For instance, equity indicator scores for root causes of disparities (*Accessibility* and *Legacies of Discrimination*) were higher for CPs than HMPs. All HMPs included maps and data on hazards; however, CPs rarely mentioned or included maps that identified the presence of hazards. HMPs and CPs should be constructed jointly. Siloed plans cause missed opportunities to determine inequalities in disaster risks.
- **Use multiple quantitative metrics to assess marginalization and needs within and across communities.** Existing metrics yield divergent results regarding social vulnerability with a little empirical basis for when to use and when. Post-disaster data can provide insight into what metrics are empirically related to outcomes of interest.
- **Include community voice to gain a more holistic perspective.** Our literature review suggests that community voices are vital and should be deemed experts. The research notes that marginalized populations are often left out of the conversation of disaster risk management for their community and that more work needs to be done to ensure they are included and held in equal

esteem with government officials. We recommend conducting interviews with members of the community who are typically excluded to ensure that communal recovery encompasses diverse voices.

More work is needed to understand the most useful data sources to assess vulnerabilities and improve the measurement of outcomes for marginalized communities that will guide resiliency and disaster recovery planning. Ultimately our goal is to progress more to the right side in Figure 2, which means equitable outcomes for the communities most in need. We argue that more work could look to integrating evidence from multiple sources within the four case study sites. This includes but is not limited to, reviewing the histories of eligibility for and access to aid, determining whether measurements used by equity indicators are considered legitimate from the perspective of marginalized people, analyzing data on other recovery program (i.e., SBA loans), and collecting the perspectives of marginalized groups impacted by hazards. Additionally, we recommend an expansion of sites to include locations nationwide affected by a variety of hazards, and various types of marginalized groups.

6. Key Themes, Questions, and Additional Readings

6.1 Outline of paper

Socially marginalized populations are often disproportionately at risk from climate hazards. This paper presents a conceptual framework for embedding equity in disaster risk management, including distinguishing between equality and equity. We apply the framework to four North Carolina communities, examining each component: historical context, plan-based indicators, social vulnerability indicators, and community voice. Our preliminary results point to inconsistencies and gaps within these components, but additional research is needed to develop the framework and supporting recommendations fully.

6.2 Key Themes

Multiple indices, metrics, and data sources are needed to measure, monitor, and determine progress to advance equitable and resilient outcomes for marginalized groups. Using one method increases the likelihood that marginalized groups are ignored and left out of receiving support.

We provide four areas that the disaster risk management community can focus on as they reach a more equitable understanding of how to meet the needs of marginalized groups. These areas are as follows,

2. Historical content related to oppression
3. Plan-based indicators
4. Social vulnerability indicators
5. Community voice

Next, we provide a section that includes discussion questions by critical dimensions. This section can assist decision-makers, emergency managers, and interested stakeholders as they re-think resilience planning with equity as its foundation.

6.3 Discussion Questions by Subject of Analysis Categories

History related to oppression:

- Looking back to history, who were the victims of oppression? (i.e., who were the winners and losers?)
- Who are the current victims of oppression?
- Who has been historically excluded from planning?
- To what extent has this stayed the same today?
- What, if any, strategies are being used to combat instances of oppression?

Plan-based indicators:

- To what extent are comprehensive plans, hazard mitigation plans, and other plans coordinated using equity indicators?
- To what extent are there opportunities to share different databases used by other plans that would foster improved measurement and better determination of the vulnerability of marginalized populations?
- How, if at all, do plans go beyond using indicators that measure symptoms of unequal vulnerability (i.e., income, poverty) to indicators that measure root causes of disparities that deal with racism and segregation (i.e., access to opportunities, legacies of discrimination)?
- Vulnerability Indices
- What indicators are currently used to identify groups that may face disproportionate risks? Are there other indicators that could provide a complementary perspective?
- What criteria are currently used to target hazard mitigation or disaster recovery resources?
- In the aftermath of past events, how have recovery resources been distributed with respect to indicators of marginalization and need?
- What factors could lead to the current distribution of recovery resources, such as individual or neighborhood capacity, political power, or past experience with disasters?

Voice:

- Who is included in the planning process? Which voice is most common (e.g., government officials, residents, etc.)?

- Who is left out? Whose voice is least common?
- How, if at all, are local organizations engaging community members?
- What lessons can be learned from community mobilization efforts made by non-governmental organizations, faith-based organizations, and others?

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Convergence of Participatory Research and Technology Innovation in Flood and Community Resilience

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Abstract

This chapter explores the growing convergence of participatory research methods and technological innovation in advancing flood resilience. As climate change intensifies the frequency and severity of flood events, there is an urgent need to bridge top-down technological solutions with bottom-up community engagement. Federal initiatives such as the National Science Foundation's Civic Innovation Challenge (CIVIC), in partnership with the Department of Homeland Security and the Department of Energy, have catalyzed a new generation of projects that integrate sensor networks, data platforms, and predictive models with community-led planning and equity-centered design. Highlighting case studies such as the flood insurance affordability project led by the University of Pennsylvania and the Navajo Nation's flood sensor deployment in Arizona, this chapter demonstrates how collaborative innovation can reshape risk governance, enhance local capacity, and build trust in flood-prone communities.

1. Introduction: Reimagining Resilience through Convergence

For decades, flood resilience efforts in the United States have been dominated by technical disciplines—hydrology, engineering, and emergency management—and governed by institutional hierarchies that emphasize risk assessment, infrastructure protection, and post-disaster recovery. While these approaches have contributed to measurable safety gains, they often neglect the social, cultural, and economic dimensions of vulnerability that shape how risk is experienced and addressed at the community level.

In response, researchers, practitioners, and policy leaders are increasingly embracing a convergence framework, bringing together participatory design, civic science, and technological innovation to co-produce flood resilience solutions. The convergence model recognizes that neither communities nor technologies alone can solve complex challenges such as flood risk. Instead, solutions must emerge from sustained, equitable partnerships that integrate lived experience, scientific insight,

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and cutting-edge tools.

This convergence framework is both philosophical and operational. It invites new ways of knowing—valuing experiential, cultural, and Indigenous perspectives alongside engineering models and geospatial data. It also requires institutions to reconfigure how projects are initiated, governed, and evaluated—shifting power toward communities while enabling transdisciplinary collaboration.

The National Science Foundation's Civic Innovation Challenge (CIVIC) exemplifies this new model. As a multi-agency initiative launched in 2020 by NSF, DHS Science and Technology Directorate, and the Department of Energy, CIVIC funds short-term, high-impact research projects that engage local governments, community-based organizations, and universities in developing and testing scalable resilience technologies (NSF, 2023). Projects range from predictive analytics for climate hazards to infrastructure monitoring systems and digital tools for civic engagement. Flood resilience has emerged as a prominent theme across several funded pilots.

The CIVIC program challenges traditional innovation pipelines that separate research from practice by foregrounding inclusion and scalability. Instead, it invites teams to co-develop, test, and adapt solutions within real-world constraints, drawing on the expertise of public officials, grassroots leaders, private-sector actors, and technical specialists.

2. Civic Innovation in Practice: University of Pennsylvania and NYC Flood Insurance Affordability

One of the most influential CIVIC-funded projects is the collaboration between the University of Pennsylvania, the New York City Mayor's Office of Resiliency, the Center for New York City Neighborhoods, and Guy Carpenter & Company, a global reinsurance broker. This team focused on the urgent problem of flood insurance affordability among low- and moderate-income (LMI) households in the New York metropolitan region, where thousands of residents face increasing premiums under FEMA's Risk Rating 2.0 framework (Guy Carpenter, 2021).

The project used geospatial analytics and community engagement to identify LMI households at high risk of losing flood insurance coverage. Through participatory workshops and policy modeling, the team co-developed pilot strategies such as means-tested flood insurance subsidies, community parametric insurance pools, and public outreach campaigns. The project also evaluated risk communication tools tailored to renters and multi-family property owners who are often excluded from traditional outreach.

The initiative not only mapped exposure but also examined social vulnerability, integrating census tract-level income, housing tenure, and linguistic isolation data to pinpoint where conventional outreach might fail. In doing so, the project addressed one of the core critiques of flood insurance reform: that technical fairness does not guarantee social equity.

By integrating actuarial modeling with qualitative insights, the project produced a

replicable framework for cities seeking to improve insurance access and equity in the face of climate-driven rate reform. Moreover, the inclusion of private-sector partners such as Guy Carpenter highlighted the potential for public-private innovation in addressing systemic risk financing challenges.

3. Sensor Innovation in Indigenous Communities: The Navajo Nation Pilot

Another CIVIC pilot demonstrating convergence is the Navajo Nation flood sensor initiative in Arizona. In this project, Arizona State University partnered with the Navajo Department of Emergency Management and tribal chapters to co-design and deploy a low-cost flood monitoring system tailored to rural, underserved environments. The sensors were adapted from models developed by the DHS Flood Apex Program but modified for solar-powered operation and low-bandwidth data transmission.

What set this initiative apart was its deep investment in local engagement. Community members were involved in sensor siting, maintenance planning, and data interpretation. Training sessions focused not only on technical skills but also on integrating sensor data into traditional ecological knowledge and community-based emergency protocols (ASU, 2022).

In community discussions, elders emphasized the importance of understanding how flood patterns had changed across generations, and how traditional seasonal markers, such as changes in plant or animal behavior, could be reconciled with sensor thresholds. This dialogic integration of data and worldview exemplified the convergence model in practice.

Through workshops and iterative design, the project fostered local ownership of both the technology and the response strategies it informed. Early outcomes included enhanced flood situational awareness in areas with no legacy gauge infrastructure and stronger relationships between emergency managers and residents.

The Navajo pilot underscores the importance of cultural relevance and accessibility in resilience technology. Rather than treating the community as an end user, the project framed residents as co-designers, ensuring the tools addressed both practical and social dimensions of flood risk.

These case studies illustrate the future of convergence not only as interdisciplinary science but also as civic practice—one that cultivates dignity, agency, and shared responsibility in the face of climate volatility.

4. Expanding the Convergence Field: Insights from Recent Literature

Recent studies reinforce and expand the value of convergence models in disaster resilience. For example, a study of civic environmental monitoring systems emphasizes that participatory technology design fosters trust and increases uptake of

decision support tools (Miller et al., 2022). These systems are most effective when community partners influence the platform architecture, data collection priorities, and visualization methods, ensuring usability and equity.

Similarly, research in *PLOS ONE* found that participatory risk mapping in urban flood-prone areas enhanced public awareness and institutional responsiveness. Community-led hazard identification exercises helped to bridge data gaps that traditional top-down mapping failed to capture, especially in rapidly changing informal settlements (Islam et al., 2023).

A separate environmental science study by Roy et al. (2024) examined hybrid knowledge systems in participatory flood planning. The authors found that resilience strategies grounded in scientific modeling and local knowledge systems led to better adoption of early warning systems, particularly in linguistically and culturally diverse areas. The key was integrating technologies with local interpretive frameworks, a principle echoed in the Navajo Nation pilot.

Other research has extended the convergence concept further into community empowerment and adaptive governance. Hendricks et al. (2022) argue that to move beyond tokenistic engagement, participatory approaches must climb Arnstein's ladder of citizen participation, advancing toward shared decision-making and control. They propose a framework where community science is institutionalized as outreach and as a governance model for infrastructure and hazard mitigation planning.

Likewise, White, Torres, and Williams (2021) highlight the role of civic data partnerships in expanding the reach and legitimacy of community-generated data. Their case study of a flood mapping initiative illustrates how shared control over data infrastructure, platform access, visualization tools, and interpretation can increase responsiveness to community needs.

Tuler et al. (2020) consider participatory modeling a tool for mutual learning, emphasizing the value of uncertainty as a shared space for exploration and trust-building. They argue that participatory vulnerability assessments are not just exercises in data co-production but catalysts for social learning and long-term institutional change.

Soden and Palen (2018) offer a critical view from the crisis informatics field, urging researchers to look beyond the mere provision of tools and consider how digital systems mediate power during crises. Their work warns against uncritical technological optimism and calls for greater scrutiny of whose interests are served by emerging crisis data infrastructures.

Together, these studies emphasize that convergence is not simply a methodological innovation but a political and institutional realignment. It transforms who gets to ask the questions, who sets the agenda, and who benefits from the answers.

5. Participatory Design and the Future of Flood Resilience

These CIVIC projects illustrate a broader shift in flood resilience from passive risk recipients to empowered co-creators of solutions. This shift requires not only novel

technologies, but also rethinking governance, funding structures, and epistemologies of risk. Participatory research methods—such as design thinking, scenario co-development, and community mapping—are becoming central to resilience innovation.

Recent contributions to the literature further elaborate on the mechanics and implications of this participatory turn. In addition to participatory modeling approaches that build mutual learning and trust (Tuler et al., 2020), digital technologies are increasingly deployed in ways that reflect and amplify community agency. Soden and Palen (2018) caution that while crisis informatics tools are often lauded for their efficiency, they may inadvertently entrench top-down power structures unless designed with community input and critical oversight.

White, Torres, and Williams (2021) demonstrate how civic data partnerships can help address this risk by centering historically excluded communities in flood planning processes. By establishing shared governance over data infrastructure, such as who collects, analyzes, and controls access to flood information, they show that trust and local agency can be rebuilt through collaboration.

The field is also moving toward a more expansive understanding of accountability. Hendricks et al. (2022) emphasize the need to climb Arnstein's ladder in engagement and institutional practice. When communities help define success metrics and evaluation criteria, research becomes more transparent, and outcomes align with local priorities. This principle is echoed in recent calls for "co-evaluation" strategies where impact is judged through community narratives and quantitative indicators.

Federal agencies can support this paradigm shift by enabling more flexible funding mechanisms, encouraging transdisciplinary partnerships, and mandating equitable data practices. As CIVIC has shown, convergence thrives when innovation is not just a matter of technological prowess, but also of shared values and mutual respect.

6. Conclusion: Converging for Climate Resilience

As climate-driven floods become more frequent and disruptive, the path to resilience must be paved with inclusion, innovation, and integration. The convergence of participatory research and emerging technology offers a promising paradigm—one that honors local knowledge, accelerates technical advancement, and strengthens trust in disaster governance.

Whether in dense urban neighborhoods grappling with flood insurance inequities or remote tribal lands deploying sensor arrays, the lessons are clear: resilience is not something communities are given; it is something they build together.

As Hendricks, Meyer, and Wilson (2022) argue in their framework of community science and flood resilience, the effectiveness of participatory technology depends on inclusion and community control. Drawing on Sherry Arnstein's ladder of citizen participation, they highlight how many hazard mitigation efforts remain stuck in tokenistic modes of engagement. True convergence—where communities actively shape, implement, and govern technology requires movement toward the upper ladder

rungs, where residents exercise meaningful power over infrastructure decisions.

Integrating this lens into flood innovation efforts ensures that tools are catalysts for equity, not just efficiency. It also highlights the need for convergence to evolve beyond a funding strategy into a sustained institutional commitment. As such, federal programs like CIVIC can serve as models for embedding shared governance, participatory evaluation, and interdisciplinary co-production into the architecture of climate resilience for years to come.

7. Key Themes, Discussion Questions, and Additional Readings

7.1 Key Themes

1. Equity-Centered Innovation: Convergence emphasizes that flood resilience must center social equity, especially in underserved communities facing disproportionate risk.
2. Community Co-Design: Participatory methods shape effective technologies that empower residents as designers, testers, and stewards.
3. Integration of Knowledge Systems: Scientific modeling is strengthened with Indigenous knowledge, lived experience, and local storytelling.
4. Scalable Prototypes: Projects like CIVIC demonstrate that scalable resilience requires iterative design within place-based contexts.
5. Institutional Realignment: True convergence requires shifting from top-down planning toward collaborative, interdisciplinary governance models.

7.2 Discussion Questions

1. How does the convergence model reshape traditional relationships between experts, agencies, and communities?
2. What design principles are most critical when creating resilience tools for culturally diverse or linguistically isolated populations?
3. How can federal programs like CIVIC ensure short-term innovation projects create lasting institutional change?
4. What role should private sector partners play in public resilience initiatives, especially those involving risk transfer mechanisms like insurance?
5. How can participatory technology design enhance trust and technical efficacy in flood-prone communities?

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Future Considerations for Homeland Security, Emergency Management, and Public Safety

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The coming decades will challenge homeland security, emergency management, and public safety systems in profound and unprecedented ways. As climate impacts intensify, infrastructure ages, technologies evolve, and threats diversify—from cyberattacks and disinformation to catastrophic floods and compound hazards—so too must the nation's approach to risk reduction and resilience. While progress has been made across all levels of government, the work ahead demands not only innovation in tools and technologies, but a deeper realignment of governance, investment priorities, data integration, and community engagement. These shifts will define the future of national preparedness and determine whether the United States remains adaptive in the face of escalating disasters.

This volume has brought together some of the most significant developments in the science, technology, and practice of flood resilience. From the foundational investments made by the DHS Science and Technology Directorate to the applied efforts of researchers, engineers, and local officials, each chapter contributes to a clearer understanding of where the nation stands—and where it must go. Section 1 traced the origins and mission of the DHS Flood Apex Program, establishing a strategic R&D framework to address the mounting risk and cost of flood events across the country. The program's emphasis on reducing fatalities, uninsured losses, and data fragmentation offers a blueprint for future applied science initiatives.

Section 2 explored how mutual aid coordination, capacity building, and smarter response technologies are reshaping how communities manage cascading flood emergencies. These chapters demonstrated that interoperability and scalable tools are not just technical goals—they are prerequisites for life-saving coordination under pressure. Case studies from Kentucky, North Carolina, and Colorado showed the tangible benefits of low-cost sensors, integrated resource management platforms, and geospatial applications deployed in real-world flood scenarios.

Section 3 expanded the focus to long-term resilience and recovery. Chapters on atmospheric flood drivers, hydrodynamic modeling, and remote sensing underscored the need for scientific precision in anticipating extreme events. Others demonstrated how historic case studies, such as Hurricane Floyd and Hurricane Matthew in North

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Carolina, can inform more targeted mitigation and recovery investments. The FloodAdapt decision-support framework presented in this section shows how user-centric tools can guide local governments through the complexities of flood risk reduction in urbanized, high-growth regions.

Section 4 turned to the economic dimension of resilience—specifically, the persistent insurance gap and the behavioral, policy, and financial drivers behind it. Here, authors examined why millions of households in high-risk areas remain uninsured, the limitations of the National Flood Insurance Program, and the innovation potential in private sector products and risk transfer tools. The importance of risk perception, actuarial modeling, and incentive design emerged as central themes for closing the protection gap and advancing household and business resilience.

Section 5, looking toward the horizon, examined what it means to truly future-proof society from flood. This section covered advances in flood modeling validation, structured data for decision-making, and standards for flood-proofing technologies. Importantly, the social equity dimensions of resilience were brought to the fore—highlighting how access to data, funding, and risk information remains uneven across vulnerable populations. The convergence of participatory research and emerging technologies revealed a critical lesson: innovation must not only be cutting-edge—it must be inclusive.

As we plan for the future, one of the foremost considerations is the increasing complexity and interconnectedness of hazards. Natural disasters no longer exist in isolation. A severe flood may now trigger chemical spills, supply chain failures, cyberattacks on emergency systems, or civil unrest in underserved areas, each compounding the overall burden. DHS, FEMA, and local responders must prepare for singular threats and multidimensional, cascading risk scenarios. Traditional, siloed planning and single-hazard mitigation strategies are no longer sufficient. Future systems must embrace integrated risk analytics, scenario-based planning, and dynamic threat modeling that spans physical, digital, and social domains.

In this context, the role of science and technology is paramount. The chapters in this book illustrate how targeted Research, Development, and Innovation (RD&I) initiatives have delivered scalable, impactful solutions. From predictive modeling and high-performance computing to low-cost sensors and situational awareness platforms, these technologies are redefining how we detect, respond to, and recover from disasters. The future requires more than isolated innovation; it calls for sustained, coordinated scientific investment across the public safety spectrum. Technologies such as artificial intelligence, digital twins, and virtual simulation must be brought into closer alignment with real-world operational needs.

As we progress toward the next decade, several critical research questions remain unresolved and warrant focused investigation. How can we improve the granularity and accuracy of structure-level flood risk models while maintaining cost-efficiency and usability for local planners and insurers? What are the long-term behavioral drivers behind household decisions on flood insurance uptake, and how can risk communication strategies be better designed to shift perception into action? How do

compounding risks, such as wildfire-flood sequences or simultaneous infrastructure failures, reshape traditional mitigation and emergency management paradigms? Moreover, what role can emerging technologies such as digital twins, immersive simulation, and AI-enabled foresight tools play in democratizing access to flood information and preparedness strategies? The intersection of flood risk and social vulnerability also remains understudied, particularly in relation to historically marginalized communities, informal housing, and climate migration pathways. Answering these questions will require interdisciplinary collaboration and a renewed commitment to translating research into practice through applied science, iterative field testing, and policy feedback loops.

Data will remain a foundational pillar of progress. The fragmentation of data across jurisdictions and sectors remains a central barrier to effective disaster management. Future resilience will depend on creating and maintaining shared data ecosystems—interoperable platforms that allow secure, real-time exchange of risk information. Standardization, common metadata frameworks, and collaborative governance mechanisms will be essential, especially as national datasets such as the National Structures Inventory become central to risk modeling, insurance, and zoning decisions.

Governance structures must evolve as well. DHS, FEMA, and local governments must strengthen coordination and reduce duplication across grants, platforms, and recovery tools. Strategic foresight must become a standard institutional function, embedding long-term planning and anticipatory decision-making into everyday operations. At the same time, equity and inclusion must be infused throughout these systems, from allocating resources to designing alert systems, recovery programs, and decision-support tools.

Finally, the future demands a new narrative. One that reframes resilience not as a cost but as an investment that builds health, safety, prosperity, and opportunity for future generations. Floods, fires, hurricanes, and cyberattacks are not isolated crises, but stress tests of a nation's foresight, leadership, and commitment to its people. The accurate measure of homeland security is not just in how we defend against harm, but how we reduce vulnerability, increase cohesion, and adapt to uncertainty.

In closing, this volume offers more than a snapshot of current progress, it charts a course forward. The chapters within represent the work of a national community of researchers, practitioners, policymakers, and innovators committed to the long-term safety and resilience of the United States. Together, they provide the insights, tools, and vision needed to face a future that is already arriving. The path ahead will require courage, clarity, and collaboration. However, the foundation has been laid—and the momentum must now be sustained.

About the Author



David J. Alexander, Ph.D. is a senior technologist and nationally recognized expert in disaster resilience, emergency preparedness, and geospatial science and technology. With over 25 years of experience spanning federal and state government, he serves as Senior Science Advisor at the U.S. Department of Homeland Security's Science and Technology Directorate, where he leads strategic efforts to advance resilience, infrastructure protection, and homeland security innovation.

He was the Department's first appointed Geospatial Information Officer (GIO), directing enterprise-wide strategies for spatial data integration, situational awareness, and technology modernization across DHS components including FEMA, CBP, CISA, I&A, and the U.S. Coast Guard. He also co-chairs the Subcommittee on Resilience Science and Technology under the National Science and Technology Council (NSTC), Executive Office of the President, where he coordinates national research efforts on cross-sector resilience and preparedness.

Dr. Alexander's leadership has shaped national initiatives in catastrophic risk analysis, crisis response coordination, geospatial information and technology, and homeland security research and development. His contributions have been recognized with the U.S. Presidential Rank Award (2022), the DHS Under Secretary for Science Excellence Award (2018, 2025), and designation as a Top 20 Influencer in GeoInsurance.

He is the creator and lead author of the America's Fault Lines series—a multi-volume exploration of the fractured geography of the United States. The series

begins with two foundational works: Disaster Nation, a sweeping diagnostic of institutional failure and emergency misgovernance, and The New Geography of Homeland Security, which reconceptualizes national security as a spatial project structured by five core geographies—sovereignty, power, risk, protection, and exclusion. Subsequent volumes examine key fault lines in American governance and infrastructure, from cascading interdependence and border sovereignty to strategic surprise and spatial injustice. A final set of instructional companion volumes translates these concepts into applied tools for spatial analysis, scenario design, and ethical GeoAI.

Through this body of work, Dr. Alexander challenges the myth of geography as neutral. His writing reveals how space is produced—by policy, data, infrastructure, and imagination—and how the distribution of risk, security, and aid reflects deeper structures of power. Across the series, he offers both a critical lens and a strategic map for understanding and reimagining the American republic.

Dr. Alexander holds a Ph.D. from George Mason University, master's degrees from Colorado Technical University and the University of South Carolina, and a bachelor's degree (cum laude) from the University of South Carolina Aiken. He also serves as adjunct faculty at Delta State University and remains a leading voice in applying science and technology to the complex realities of risk governance in the 21st century.